Climate Change and Building Energy Use:

Evaluating the impact of future weather on building energy performance in tropical regions

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Abstract

Trends in average global temperature changes show that the climate is undeniably warming. The Intergovernmental Panel on Climate Change (IPCC) predicts that global temperatures will increase by a range of 1.1°C to 6.4°C by the end of the twenty-first century. For tropical climate zones, increases in global temperatures cause increases in building heat gain, which lead to increases in annual cooling energy use and poorer thermal comfort. This project evaluates the impacts of future climate change on the HNEI Frog building's energy performance to determine the most effective envelope design now and for the future. Three designs models were created and compared: the Current Design model, the ASHRAE 90.1-2010 Standard Design model, and the Proposed Design model. Using the climate change future weather data methodology, building energy use and cooling loads were compared for three time periods, present-day, 2050, and 2080, under the IPCC A2 emissions prediction scenario. The hypothesis was that the Proposed Design model, due to higher levels of insulation, would perform better than the Current Design in each time period, reducing annual energy use.

The methodology of this research can be applied to studies that examine a number of building design features, including but not limited to thermal mass, window-to-wall ratio, glazing material, overhang shading, green roof systems, and natural ventilation strategies. With today's emphasis on reducing building energy use and on sustainability, it is essential to understand how building envelopes will perform in the future.

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List of Abbreviations

AOGCMs	Atmosphere-Ocean General Circulation Models
AR3	Third Assessment Report
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
BC	Black Carbon
BES	Building Energy Simulation
CBECS	Commercial Buildings Energy Consumption Survey
CIBSE	Chartered Institution of Building Services Engineers
CCWorldWeatherGen	Climate Change World Weather Generator
DDC	Data Distribution Centre of the IPCC
DHW	Domestic Hot Water
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EPW	EnergyPlus/EPSr Weather
GHGs	Greenhouse Gases
HadCM3	Hadley Centre Coupled Model, version 3
HNEI	Hawai‘i National Energy Institution
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LSAT	Land-surface Air Temperature
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Data Base
SERG	Sustainable Energy Research Group
SRES	Special Report on Emissions Scenarios
SRI	Solar Reflectance Index
SSR	Surface Solar Radiation
SST	Sea Surface Temperature
TMY	Typical Meteorological Year
TMY2	Typical Meteorological Year 2

TMY3	Typical Meteorological Year 3
UKCIP	UK Climate Impact Projection
UKCIP02	UK Climate Impact Projection 2002
UKCP09	UK Climate Projection 2009
UN	United Nation
UNEP	United Nations Environment Programmed
WMO	World Meteorological Organization

Chapter 1: Introduction

1.1 Background

Buildings are chiefly planned, designed, and operated, using systems that are heavily power-driven, to provide indoor comfort for the occupants regardless of exterior climate conditions. Heating, ventilation, and air conditioning (HVAC) are a trio of systems that manage indoor and vehicular environmental climate in order to provide thermal comfort and acceptable indoor air quality. The cost of these systems to a building, however, is excessive. The HVAC system alone spends 50% of a building's overall energy consumption and 20% of the total energy consumption in the United States.[1] As a result, the cost of operating and maintaining buildings is increasing with time.

Buildings consume a large amount of energy, which comes primarily from non-renewable resources. Carbon dioxide (CO_2) emissions, along with other pollutants, are by-products of these energy sources and contribute to global warming. Buildings in Europe account for 37% of the total energy consumption for residential and commercial sectors; in the United States, this can be as high as 40%.[2] Warnings about the effects of global warming and the depletion of non-renewable resources have inspired a movement toward developing more energy-efficient, high-performance buildings.

Weather data are important in estimating a building's energy usage and thermal comfort performance. Using weather data to analyze energy consumption and help design buildings is becoming increasingly important. Unfortunately, current practices use standard, present-day weather files for building simulations; this practice does not take into consideration the rapidly changing climate and the potential future impacts of these

[1] Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information." *Energy and Buildings* 40, no. 3 (2008), 394.
[2] Ibid., 396.

changes on the building.[3] The implications of the changing climate on building performance need to be considered in future building projects in order to choose proper materials and design thermal mass and building services that will weather the changes.[4]

For building simulation programs that predict climate conditions, techniques have been developed that adjust current weather files to reflect climate change scenarios predicted by the Intergovernmental Panel on Climate Change (IPCC) in the 2007 "Fourth Assessment Report" (AR4). Stephen Belcher, a professor of meteorology and head of the Met Office Hadley Centre for Climate Science and Services, proposes a "morphing" technique, which generates "climate change weather files for world-wide locations ready for use in building performance simulation programs."[5] The climate change world weather file generator (CCWorldWeatherGen) together with Meteonorm implement the 2001 IPCC AR3 model summary of the Hadley Centre Coupled Model, Version 3 (HadCM3) to generate future weather data for use in building energy simulation (BES) programs. This dissertation project will use these to generate climate change weather files for the years 2050 and 2080.[6]

1.2 Project Statement

Because of the rapid climate change our planet is undergoing, it is becoming increasingly important to consider climate predictions when designing the building envelope for new buildings, building renovations, and investment planning. BES programs are designed to test how a building will perform under changing climate

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[3] Jentsch, Mark F., AbuBakr S. Bahaj, and Patrick A.B. James. "Climate change future proofing of buildings - Generation and assessment of building simulation weather files," *Energy and Buildings* 40, no. 12 (2008), 2149.
[4] Ibid.
[5] Sustainable Energy Research Group. University of Southampton. "Climate Change World Weather File Generator for World-Wide Weather Data – CCWorldWeatherGen." October 2013. http://www.energy.soton.ac.uk/ccworldweathergen/ (accessed March 25, 2015).
[6] Ibid.

conditions and can be used to assess the performance of both new designs and existing buildings. Unfortunately, the use of current weather files for BES programs does not accurately assess the potential impacts of the changing climate on a building. Current weather files are only capable of predicting the building's performance for an estimate of five to ten years. During this time frame, climate change will not be significant enough to affect the building's performance. Future weather files, on the other hand, can predict climate changes, based on various IPCC predicted emissions scenarios, much farther into the future, and are thus ideal for assessing the long-term energy consumption of a building relative to the changing climate.

1.3 Objective

The main objective of this research is to introduce the use of future weather files for BES programs in order to assess current energy use and potential future performance for building improvements and new building designs. The CCWorldWeatherGen and Meteonorm use the existing EnergyPlus/Typical Meteorological Year 3 (EPW/TMY3) weather files to generate EPW/TMY2 future weather files for 2050 and 2080. These files will be used to identify and analyze the potential impacts the changing climate has on the annual energy use, heat gain, and end uses for the Frog building at the University of Hawaiʻi at Mānoa (UHM) Honolulu. The results of the study will provide the designers and building owners insight into future building performance and potential building improvements that can be implemented now.

This research will address the following four questions:

- Why is climate changing?
- How might climate change affect buildings in the future?
- Why is building energy consumption increasing?
- How might building envelope design help reduce energy consumption?
- How can future EPW weather data be created for use in BES programs?
- How might changing climate affect buildings in 2050 and 2080?

PART 1:

EXTENDED LITERATURE REVIEW

Chapter 2: Changes in Global Climate

The term global warming describes the gradual increase in the earth's average temperature, which has risen more than 0.8°C over the past 100 years and around 0.2°C per decade over the past 25 years. [7] Scientists agree that the current climate changes are largely the result of global warming. Most of the warming has been caused by manmade greenhouse gas (GHG) emissions from buildings, businesses, agriculture, and transportation. According to IPCC predictions, the global temperature increase, by the end of the twenty-first century, will range from 1.1°C to 6.4°C.

Over the past 50 years, the main causes of global warming include increasing levels of GHGs released through the non-stop burning of fossil fuels, land clearing pollution, agricultural pollution, and other human activities.[8] The GHG effect is caused by GHGs trapping and reflecting long-wave radiation in the atmosphere back down; this warms the earth's surface (Smith 2001).[9] Global warming concerns include the exhaustion of Earth's energy resources and the heavy environmental impact it is having on the climate.

This chapter will assess the scientific literature on global warming and climate change using the 2013 IPCC "Fifth Assessment Report" (AR5). IPCC's website reports that it is the world leader in the assessment of climate change and was "established by the United Nations Environment Programmed (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and social-economic impacts."

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[7] LiveScience. "Global Warming: News, Facts, Causes & Effects." 2015. http://www.livescience.com/topics/global-warming/ (accessed March 12, 2015).
[8] Ibid.
[9] Smith, Peter F. *Architecture in a Climate of Change: A Guide to Sustainable Design*. (Oxford: Architectural Press, 2001), 2.

The website goes on to explain,

> The IPCC is a scientific body… [that] reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It does not conduct any research nor does it monitor climate related data or parameters.
>
> Thousands of scientists from all over the world contribute to the work of the IPCC on a voluntary basis. Review is an essential part of the IPCC process, to ensure an objective and complete assessment of current information. IPCC aims to reflect a range of views and expertise….
>
> The IPCC is an intergovernmental body. It is open to all member countries of the United Nations (UN) and WMO. Currently 195 countries are Members of the IPCC. Governments participate in the review process and the plenary Sessions, where main decisions about the IPCC work programme are taken and reports are accepted, adopted and approved.[10]

2.1 Global Warming

Multiple independent climate studies from scientists all over the world indicate that the earth's climate is steadily warming. The rise of the average global surface temperature is the most noticeable indication of climate warming. Other measurable changes include changes in atmospheric and ocean temperatures; the melting of glaciers, sea ice, and land ice; and a rising sea level. The warming of land temperatures coincides with the warming of ocean air temperatures; the warming of ocean air temperatures coincides with the warming of sea surface temperatures, and so on.[11] According to the AR5,

> Observations of the climate system are based on direct measurements and remote sensing from satellites and other platforms. Global-scale observations from the instrumental era began in the mid-19th century for temperature and other variables with more comprehensive and diverse sets of observations available for the period

[10] IPCC. "Organization." n.d. https://www.ipcc.ch/organization/organization.shtml (accessed March 27, 2015).

[11] Stocker, Thomas, et al., eds. "Summary for Policymakers," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment: Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 4.

> 1950 onwards. Paleoclimate reconstructions extend some records back hundreds to millions of years. Together, they provide a comprehensive view of the variability and long-term changes in the atmosphere, the ocean, the cryosphere, and the land surface.[12]

The quantity and nature of observed global weather change since the 1950s shows that the warming of the climate is undeniable. Studies have found that human activity has caused more than half of the observed increase in average global surface temperature. The release of CO_2 into the atmosphere, by the burning of fossil fuels among other things, is the single largest contributor to global warming. Greenhouse gases and aerosols affect the climate by altering incoming solar radiation and outgoing thermal radiation, part of the earth's energy balance. The overall effect of human activity on climate has been an exacerbation of the warming already occurring from other natural processes such as solar changes and volcanic eruptions. Because the concentration of both natural and manmade GHGs has increased, the temperatures of the atmosphere and ocean are increasing as well, snow and ice are diminishing, and sea levels are rising.[13]

We can notice the climate changes by simply observing the year-to-year differences in the environment around us. The temperature increases of the atmosphere and ocean, and the increased amounts of GHG emissions, are just two indicators of climate change. Although, each decade is not always warmer than the previous, evidence shows an overall increase in average global surface temperature since we began measuring in the nineteenth century. This increase is an early indicator of climate change and many scientists from all over the world have independently confirmed that the climate is indeed changing. Multiple studies and much research show us that the world is warming, from the heights of the atmosphere to the depths of the ocean. The following sections of this chapter will examine the changing climate variables, including surface temperature, atmosphere water vapor, ocean temperature, precipitation, glaciers, ocean, and land ice, and sea level are all indicators of climate change.[14]

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[12] Ibid.
[13] Ibid.
[14] Stocker, Thomas, et al., eds. "Observations: Atmosphere and Surface," in IPCC 2013: *Climate Change 2013: The Physical Science Basis Contribution of Working Group*

2.2 Climate Change Indicator

Even though the terms climate change and global warming are often used interchangeably, each term is distinct. Global warming refers to the increase in the earth's average surface temperature, mainly from GHGs emitted into the atmosphere by the burning of fossil fuels for energy. Greenhouse gasses, like CO_2, trap the sun's energy increasing the average temperature of the planet. This constant warming of the planet over time contributes to climate change.[15]

Climate change is a much broader term and is generally defined as average weather. It refers to the changes in weather patterns, such as increased average temperature, humidity levels, cloudiness, precipitation, and so on (see Figure 1). The rise in the average global temperature is likely to affect many of these factors. Thus, while global warming is a major influence in climate change, what most people notice is not necessarily the relatively subtle warming of temperatures but rather the more dramatic changes in climate.[16]

I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (New York: Cambridge University Press, 2013), 198.

[15] Climate Central. "What is the difference between global warming and climate change?" November 7, 2009. https://www.climatecentral.org/library/faqs/what_is_the_difference_between_global_warming_and_climate_change (accessed March 31, 2015).

[16] Ibid.

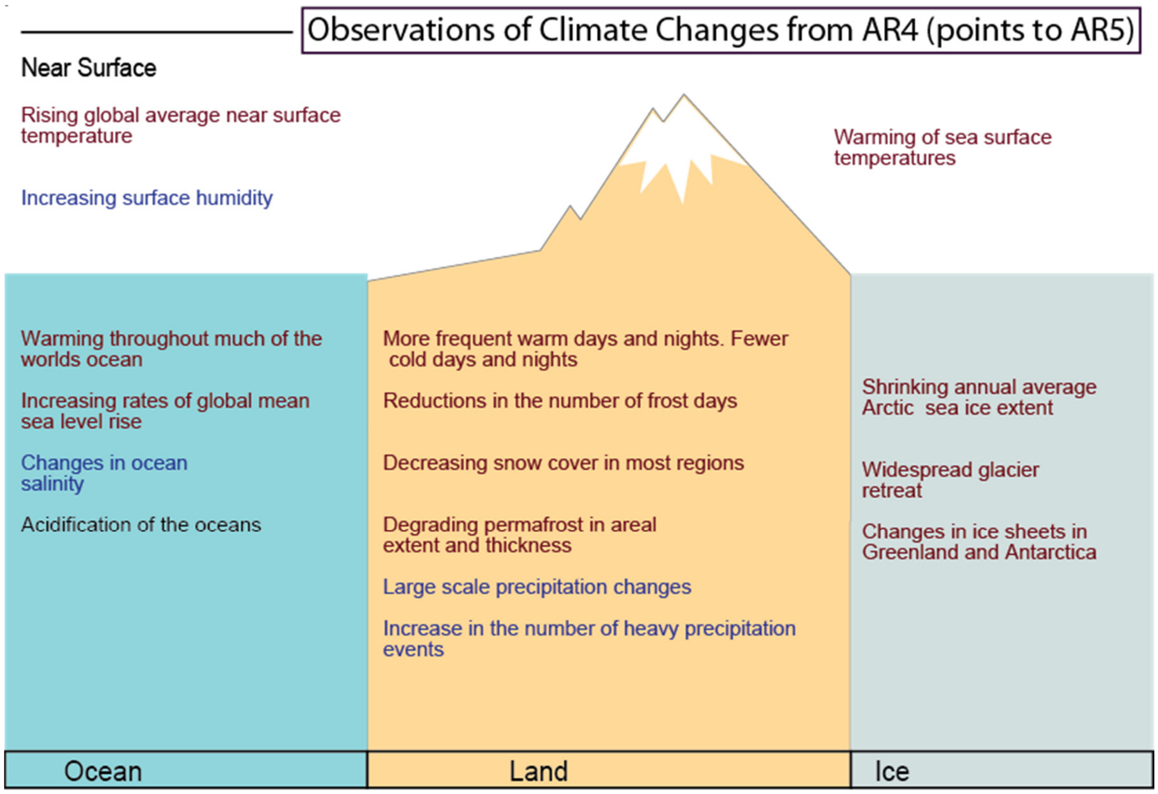

Figure 1. "Overview of observed climate change indicators as listed in AR4 (temperature: red; hydrological: blue; others: black)."
Source: Stocker, Thomas, et al., eds. "Introduction," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013): Figure 1.3, 130.

Figure 1 shows an overview of climate change according to the 2007 IPCC AR4. Based on this information, many of the key climate elements indicate changes to the climate condition as it coincides with the rise in average global surface temperature

2.2.1 Atmosphere

Since scientists began keeping record, we have found that the earth's surface temperature is increasing. The combined calculated data from land and sea has shown an increase in global earth surface temperature of 0.85°C from 1880 to 2012 (see Figure 2). The recorded data for the land-surface air temperature (LSAT) are obtained from several independent weather station observations. All agree that the LSAT has increased. The sea surface temperature (SST) data records are obtained by many methods, including through satellites, and also show an increase in SST.[17]

Since 1950, many changes relating to weather and climate events have been observed. Most analyzed global land areas have experienced significant warming of both maximum and minimum temperature extremes. The most noticeable increase the comparison of minimum temperature extremes to maximum. According to the 2013 IPCC AR5, "the increase in minimum temperature extremes compared to maximum temperature extremes is high due to the more consistent patterns of warming in minimum temperature extremes globally."[18] In general terms, this means the number of cold days and nights is decreasing. A large part of Europe, Asia, and Australia is undergoing these changes. Klein Tank, together with fifty scientists and authors, in "Observations: Atmosphere and Surface," has concluded that as the overall global temperature are increasing so too is the amount of heavy precipitation. Precipitation, a vital aspect of the earth's water cycle, delivers atmospheric water to earth. Precipitation is water released from clouds in the form of rain, snow, or hail. Since the mid-twentieth century, as the climate is warming, precipitation is increasing. More land regions will show an increase of precipitation while others will experience a decrease in precipitation. Regions, such as North America and Europe will have heavier precipitation levels while others, such as southern Australia and western Asia, will experience a decrease in precipitation.[19] Changes in precipitation will be one of the most critical factors in determining the overall impacts of global warming.

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[17] Stocker, Thomas, et al., eds. "Observations: Atmosphere and Surface," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 162.

[18] Ibid., 209.

[19] Ibid., 162.

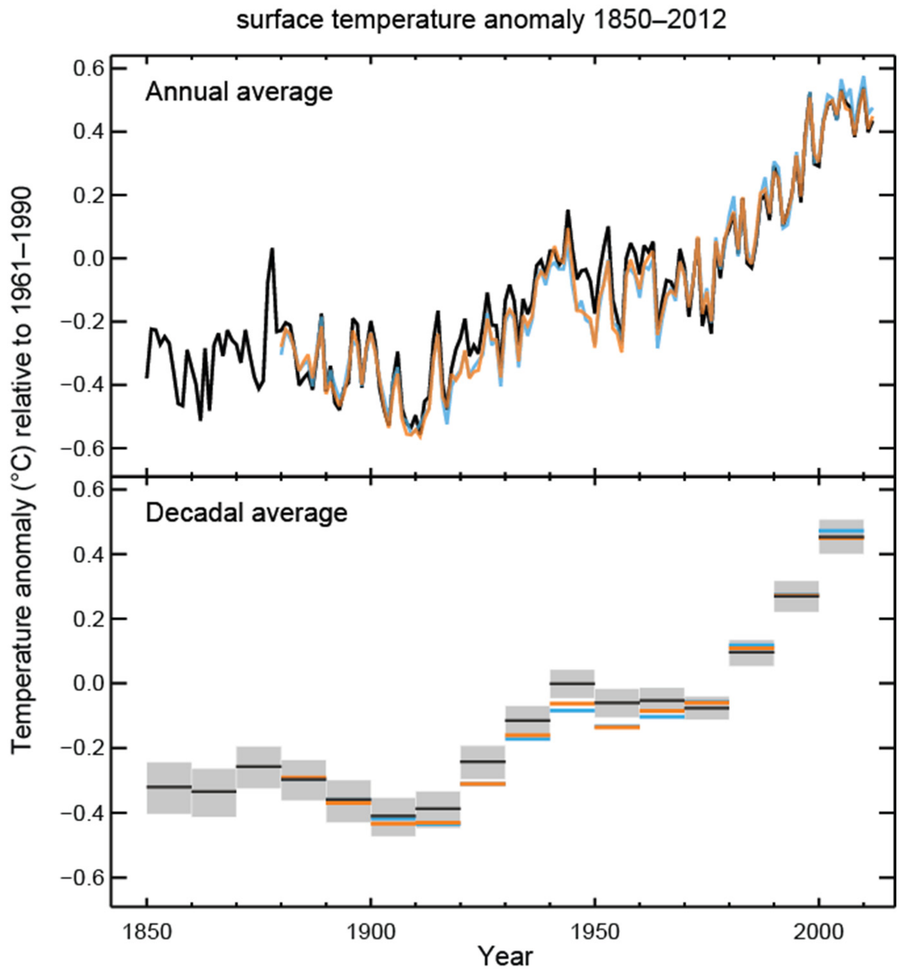

Figure 2. "Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 from three data sets. Top panel: annual mean values. Bottom panel: decadal mean values including the estimate of uncertainty for one dataset (black). Anomalies are relative to the mean of 1961 – 1990."
Source: Thomas Stocker, et al., eds. "Summary for Policymakers," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment: Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013): Figure SPM.1 (a), 6.

2.2.2 Ocean

According to the 2013 IPCC AR5, the surface of the ocean is the largest energy storage body in the climate system. The AR5 reports, "Ocean warming dominates the global energy change inventory. Warming of the ocean accounts for about 93% of the increase in the Earth's energy inventory between 1971 and 2010 (*high confidence*)."[20] The warming of the upper ocean, 0 to 700 m, accounts for about 64% of that total. The remainder of the change in global energy heat can be found in the warming of the deep ocean (29%), the warming of the continents (3%), melting ice (3%), and the warming of the atmosphere (1%) (see Figure 3).[21]

Correspondingly, measure of water expansion is an indicator of global warming. As the ocean warms, the water itself expands, which is reflected in the rise of global sea level. Over the past one hundred years, the global sea level has risen by 10 to 25 cm; much of this can be related to the increase in the global surface temperature. According to the 2013 IPCC AR5, "global mean surface air temperature has increased 0.3°C to 0.6°C over the last 100 years, with the five global-average warmest years being in the 1980s."[22] The melting of glaciers and ice sheets is evidence of the effects of global warming and further increases in global surface temperature will continue to contribute to sea level rise (see Figure 4).

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[20] Stocker, Thomas, et al., eds. "Observation: Ocean," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 257.
[21] Ibid., 199.
[22] Stocker, Thomas, et al., eds. "Introduction," in IPCC, 2013*: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 124.

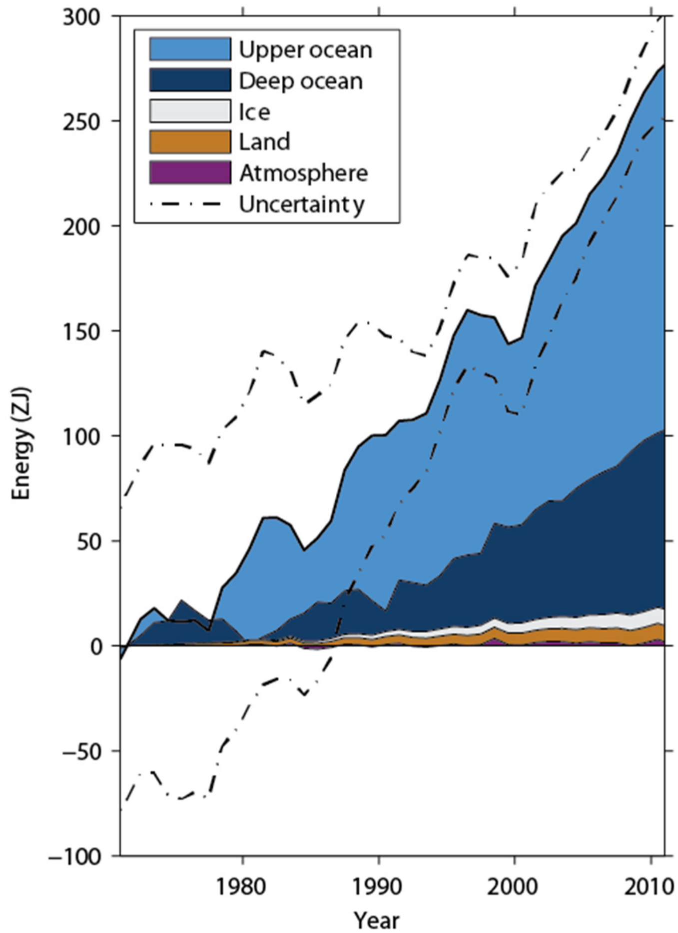

Figure 3. “Plot of energy accumulation in ZJ (1 ZJ = 10^{21} J) within distinct components of the Earth’s climate system relative to 1971 and from 1971 to 2010 unless otherwise indicated.” Upper ocean (+700 m) accumulated 64% of energy; deep ocean (-700 to -2000 m), 29%; ice melt, 3%; land warming, 3%; and atmosphere warming, 3%. Source: Stocker, Thomas, et al., eds. “Observation: Ocean,” in IPCC, 2013: *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013): Box 3.1, Figure 1, 264.

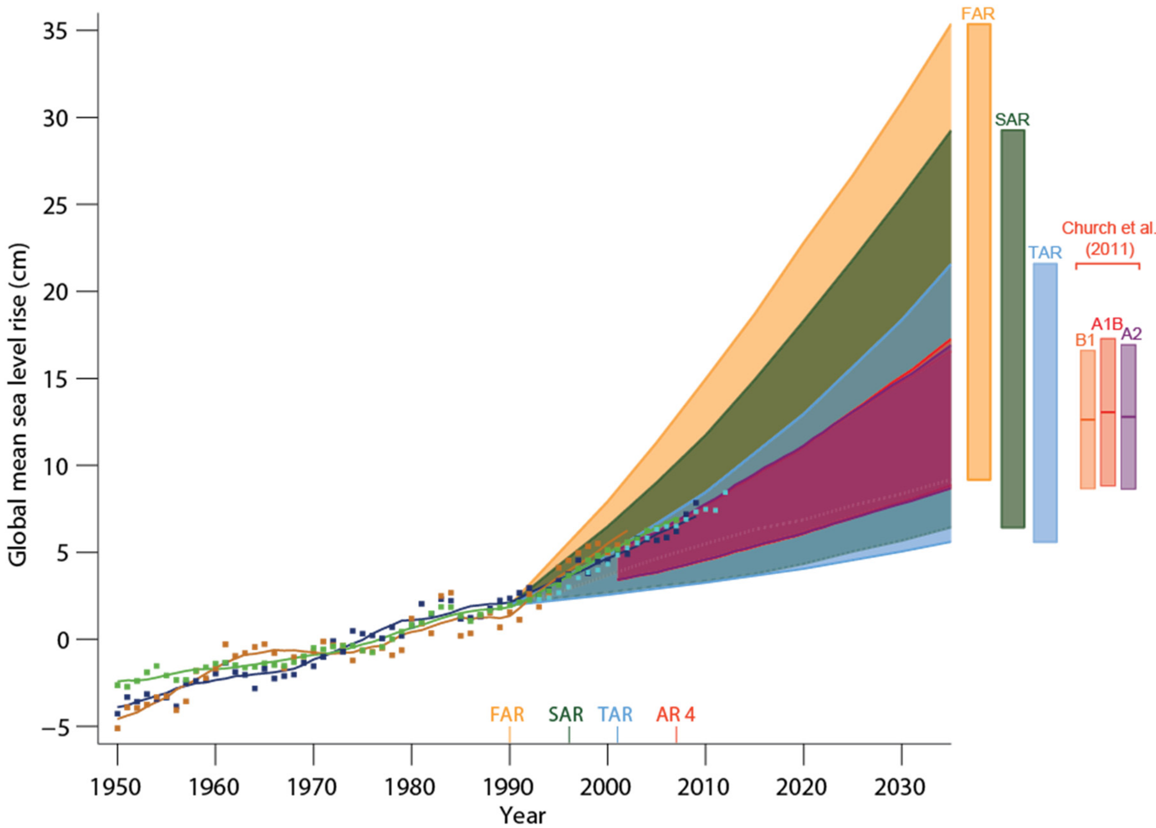

Figure 4. “Estimated changes in the observed global annual mean sea level since 1950 relative to 1961-1990.”
Source: Stocker, Thomas, et al., eds. “Introduction,” in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013): Figure 1.10, 137.

Figure 4 shows the collected research and projections of sea level rise from 1950 to 2035. The squares indicate annual mean values and the solid lines, smoothed values. The shading shows the largest model projected range of global annual sea level rise for the fifth (FAR), second (SAR), and the third (TAR) assessment reports. The authors of figure 4 used the Coupled Model Intercomparison Project Phase 3 (CMIP3) model based on the 2003 IPCC Special Report on Emissions Scenarios (SRES) for B1, A1B, and A2 projection.[23]

[23] Ibid., 137.

2.2.3 Cryosphere

The cryosphere is comprised of the frozen parts of the Earth's surface including snow, river and lake ice, sea ice, glaciers, ice shelves and ice sheets, and frozen ground, both on land and beneath the ocean. It is an integral part of the global climate system because of its sensitivity to temperature change. The nature of the cryosphere makes it something of a 'natural climate-meter' because of its responsiveness to temperature, precipitation, sea level rise, and other climate elements.[24]

The cryosphere affects the surface energy storage, the water cycle, surface gas exchange, and sea level rise. Thus, the cryosphere is a fundamental controller of the physical, biological, and social environments, over a large part of the earth's surface. The decrease of the cryosphere will have a substantial negative impact on the environment on a global scale. The 2013 IPCC AR5 reports that, "Ice sheets and glaciers exert a major control on global sea level…, ice loss from these systems may affect global ocean circulation and marine ecosystems…. Furthermore, decline in snow cover and sea ice will tend to amplify regional warming through snow and ice-albedo feedback effects…. In addition, changes in frozen ground (in particular, ice-rich permafrost) will damage some vulnerable Arctic infrastructure… and could substantially alter the carbon budget through the release of methane."[25]

2.2.4 Greenhouse gas

Present-day concentrations of atmospheric GHGs, including CO_2, methane, and nitrous oxide, far exceed the range of concentrations recorded in ice cores from the past 800,000 years. The anthropogenic emissions from our use of fossil fuel as a primary source of energy since 1750 have caused an increase in the amount of CO_2, methane, and

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[24] Stocker, Thomas, et al., eds. "Observation: Cryosphere," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 319.
[25] Ibid., 322-23.

nitrous oxide in the atmosphere. The problems caused by the higher concentrations of GHGs in the atmosphere will persist and amplify the longer we choose to rely on fossil fuels.[26] The 2013 IPCC AR5 reported an increase in concentrations of CO_2 by 40%, from 278 ppm to 390.5 ppm, between 1750 and 2011 (see figure 5). During the same time interval, methane concentrations increased by 150% from 722 ppb to 1803 ppb, and nitrous oxide concentrations increased by 20%, from 271 ppb to 324.2 ppb.[27] The continuing increase of CO_2 emissions from the burning of fossil fuel and other human activities are the dominant cause of the observed increase in atmospheric CO_2 concentrations.[28]

The continuation of anthropogenic CO_2 emissions is and will continue to put a great strain on the ocean's ecosystem. Thirty percent of the emitted anthropogenic CO_2 has been absorbed by the ocean, thus reducing the GHGs level in the atmosphere and delaying the impacts of global warming. However, over two centuries of CO_2 absorption has caused acidification of the oceans. Ocean acidification, the decrease in pH levels of the water, is expected to impact ocean species to varying degrees[29] Studies done by the Pacific Marine Environmental Laboratory (PMEL) have shown that,

> a more acidic environment has a dramatic effect on some calcifying species, including oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton. When shelled organisms are at risk, the entire food web may also be at risk. Today, more than a billion people worldwide rely on food from the

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[26] Stocker, Thomas, et al., eds. "Summary for Policymakers," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment: Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 11.

[27] Ibid.

[28] Stocker, Thomas, et al., eds. "Carbon and Other Biogeochemical Cycles," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 467.

[29] Stocker, Thomas, et al., eds. "Observation: Ocean," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 295.

> ocean as their primary source of protein. Many jobs and economies in the U.S. and around the world depend on the fish and shellfish in our oceans.[30]

Climate change and anthropogenic ocean acidification do not act independently. Increases in anthropogenic CO_2 emissions coincide with the increase of ocean acidification. Incidentally, warming of the ocean reduces the absorption capacity of the seawater, thus reducing the amount of CO_2 absorption from the atmosphere. As a result, the concentrations in the atmosphere will grow faster and we will continue to experience greater increases in global warming.[31]

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30 PMEL Carbon Program. "What is Ocean Acidification?" n.d. http://www.pmel.noaa.gov/co2/story/What+is+Ocean+Acidification%3F (accessed March 30, 2015).

31 Stocker, Thomas, et al., eds. "Observation: Ocean," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 297.

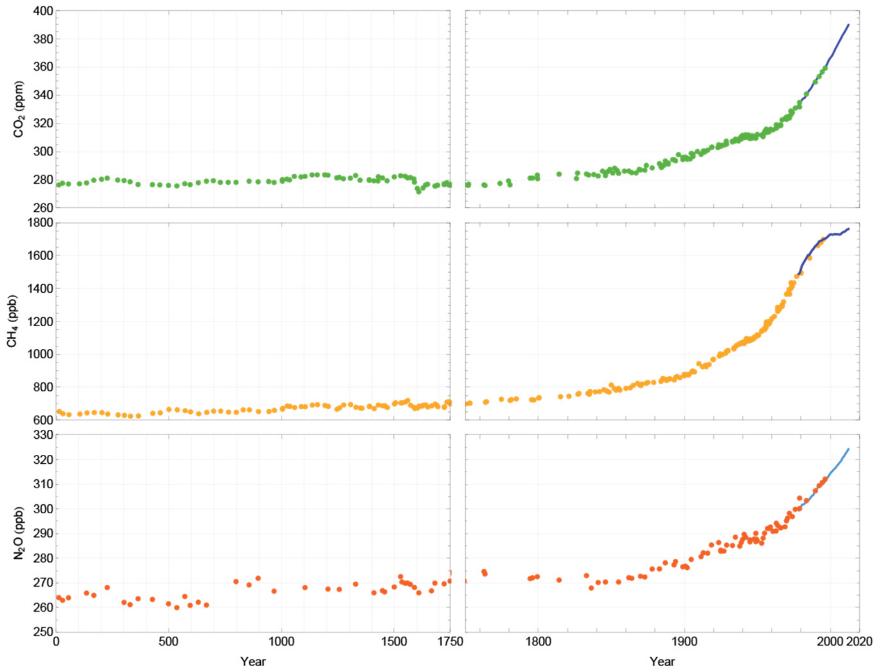

Figure 5. "Atmospheric CO_2, CH_4, and N_2O concentrations history over the industrial era (right) and from the year 0 to the year 1750 (left), determined from air enclosed in ice cores and firm air (colour symbols) and from direct atmospheric measurements (blue lines, measurements from the Cape Grim observatory)."
Source: Stocker, Thomas, et al., eds. "Carbon and Other Biogeochemical Cycles," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013): Figure 6.11, 493.

2.3 Melting of Ice in Greenland & Antarctica due to Climate Change

In *Climate Change 2013: The Physical Science Basis*, the IPCC reported on a study done on the decline of the cryosphere from the effects of climate change (see figure 6). The focus of the study was to estimate the amount of ice mass loss in Greenland and Antarctica due to climate change. The study estimated that the total amount of ice mass loss over the last twenty years, from 1992 to 2011, was substantial. Together, these locations show an estimated sum of ice mass loss to be 4260 Gt, equivalent to 11.7 mm of sea level rise.[32] Figure 3 shows the major increase in ice loss from 1998 to now and also shows the rate continuing to rise at a more rapid rate.

The ice loss in Greenland seems to be more substantial than that in Antarctica. Both locations lost about the same amount of ice mass until 2003, when suddenly Greenland outpaced Antarctica. It is possible that global warming may have more effect on the northern hemisphere than the southern. The two hemispheres may react differently to climate change. Nonetheless, global temperature is increasing and sea levels are rising as the cryosphere continues to decline.[33]

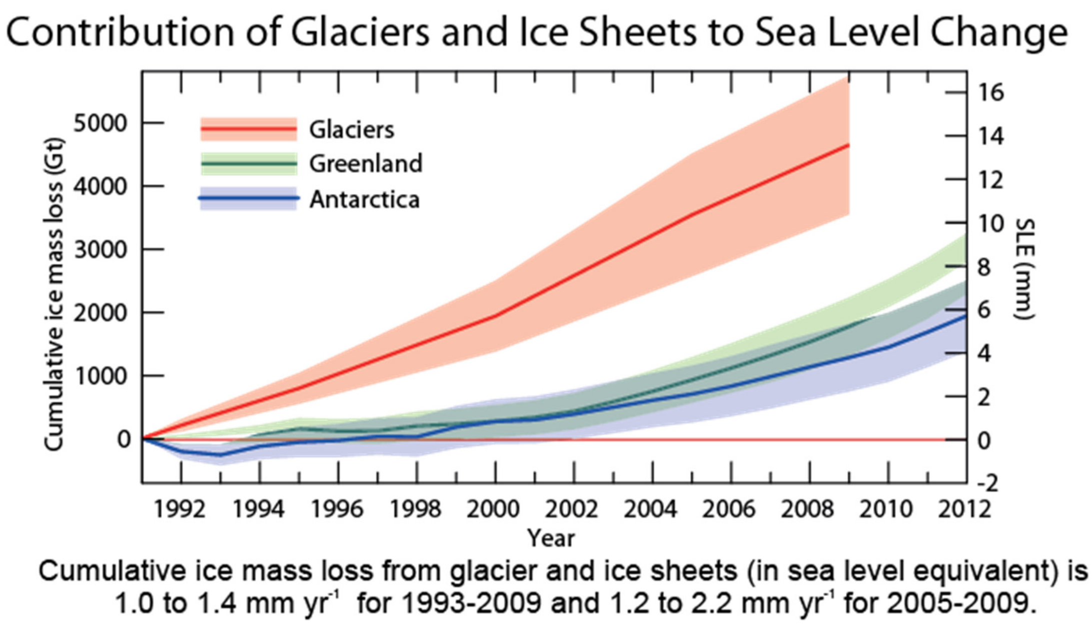

Figure 6. "Schematic summary of the dominant observed variations in the cryosphere. The […] figure summarizes the assessment of the sea level equivalent of ice loss from the ice sheets of Greenland and Antarctica, together with the contribution of all glaciers except those in the periphery of the ice sheets."
Source: Stocker, Thomas, et al., eds. "Observation: Cryosphere," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013): Figure 4.25, 367.

[32] Stocker, Thomas, et al., eds. "Obersvation: Cryosphere," in IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2013), 353.
[33] Ibid., 357.

Chapter 3: Energy Consumption

The world's energy needs are rapidly growing - an issue that has already raised concerns over the challenges of supply, the exhaustion of energy resources, and the heavy environmental impacts involved, such as global warming.[34] Energy consumption from the building sector today contributes to between 20% and 40% of global energy use, which in turn contributes directly to global warming and climate change. With the planet's population continuing to grow and spending increasing amounts of time indoors, the demand for building services will only increase. Building services are the mechanical systems of a building, including heating, lighting, power and supply, lifts and escalators, health and safety, and security and alarm systems. The day-to-day operation of these systems, especially HVAC, is a major contributor to energy consumption. With the increase in population, energy demand will surely continue to rise. For this reason, energy efficiency in buildings is, today, a leading objective for energy policy at regional, national, and international levels.

3.1 World Energy Use

There are many concerns about the growing energy demand and its implications for the environment. Buildings consume a lot of energy, which comes mostly from the burning of non-renewable resources, which releases CO_2 and other pollutants into the environment and continues to contribute to global warming. The building sector in Europe, both residential and commercial, accounts for 37% of total energy consumption. In the United States, this percentage can be as high as 40%.[35]

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[34] Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information." *Energy and Buildings* 40, no. 3 (2008), 394.
[35] Ibid., 396.

Building services require a significant amount of energy to operate. Energy consumption in buildings has been growing substantially over time. According to Luis Perez-Lombard, Jose Ortiz, and Christine Pout, in "A review on buildings energy consumption information," the primary energy demand has increased by 49%, along with a 43% increase in CO_2 emissions during the last two decades (1982-2004) at an average annual increase of 2%. Data gathered by the International Energy Agency (IEA) predicts that the current trend of energy consumption will continue to the end of this century.[36]

3.1.1 Population and economic growth contribute to energy consumption increase

The average annual energy consumption amount is increasing substantially because of the growing economies of developing countries in Southeast Asia, the Middle East, South America, and Africa. Perez-Lombard, Ortiz, and Pout identified a relationship between the increase of energy consumption and the growth of economic development along with population growth (see Table 1). They wrote,

> Interesting consequences can be obtained from the analysis of the trend of main world energy indicators between 1973 and 2004[…]: (1) the rate of population growth is well below the GDP, resulting in a considerable rise of per capita personal income and global wealth, (2) primary energy consumption is growing at a higher rate than population, leading to the increase of its per capita value on 15.7% over the last 30 years, (3) CO_2 emissions have grown at a lower rate than energy consumption showing a 5% increase during this period, (4) electrical energy consumption has drastically risen (over two and a half times) leading to a percentage increase in final energy consumption (18% in 2004), (5) efficiency in exploiting energy resources, shown as the relation between final and primary energy, has declined by 7% points, especially due to soaring electrical consumption, and (6) final and primary energy intensities have dropped because of the higher rate of growth of the GDP over the energy consumption increase ratio, resulting in an overall improvement of the global energy efficiency.[37]

[36] Ibid., 394.
[37] Ibid.

Table 1. “Global energy indexes evolution between 1973 and 2004”

Parameter	1973	2004	Ratio (%)
Population (millions)	3938	6352	61.3
GDP (G$ year 2000)	14,451	35,025	142.4
Per capita income ($ year 2000)	3,670	5,514	50.2
Primary energy (Mtoe)	6,034	11,059	83.3
Final energy (Mtoe)	4,606	7,644	66
Final energy/primary energy	0.76	0.69	-9.4
Electrical energy (Mtoe)	525	1374	161.8
Electrical energy/final energy	0.11	0.18	63.5
Per capita primary energy (toe)	1.53	1.77	15.7
Per capita CO_2 emissions (ton)	3.98	4.18	5
Primary energy intensity (toe/G$ year 2000)	418	316	-24.4

Data taken from International Energy Agency (IEA)
Source: Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information.” *Energy and Buildings* 40, no. 3 (2008): Table 1, 395.

The growth in population, building service needs, and comfort level requirements within buildings has increased building energy consumption in developing countries. Energy use in developing countries is increasing at an average annual rate of 3.2% and is expected to continue increasing at this rate or faster through 2020, according to the data gathered by the International Energy Agency (IEA).[38] The energy consumption average annual rate of increase for developed countries is slower, at 1.1% (see figure 7). Developed countries refer to North America, Western Europe, Japan, Australia, and New Zealand. Many of these countries are already actively battling against global warming, passing policies to reduce GHG emissions and seeking new energy sources, including renewable and green technologies. Despite the planning and efforts many countries are putting into reducing GHG emissions, many of the developing countries are ignoring the problems of global warming and excessive GHG emissions. The amount of energy used by developing countries will greatly contribute to global warming and climate change

[38] Ibid.

down the road. Figure 7 compares the faster growth rate in energy use in developing nations to the slower, steadier growth rate of developed nations. By 2020, developing nations will have surpassed the use of energy of developed nations, according to the IEA study.[39]

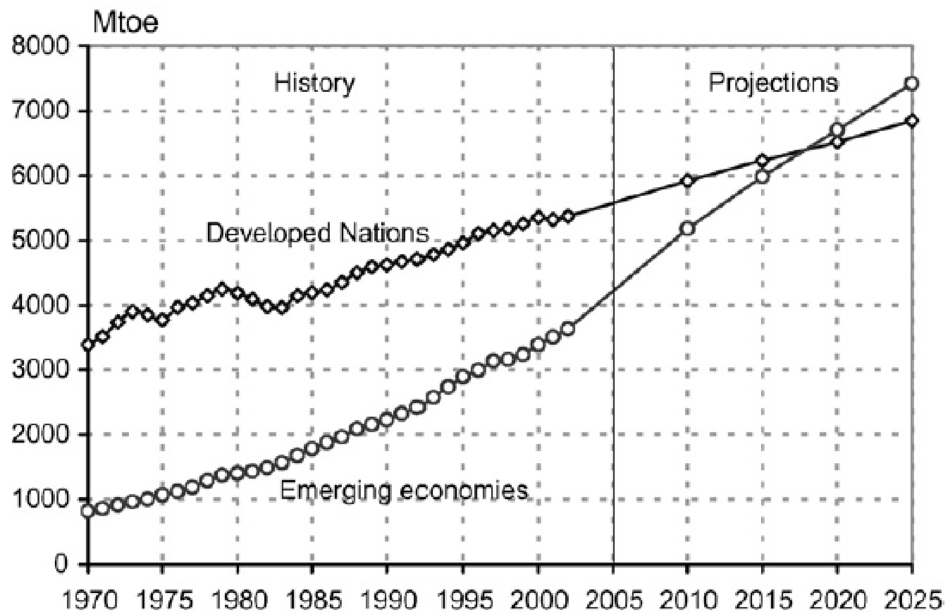

Figure 7. "World energy use of developed and developing nations".
Source: Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information." *Energy and Buildings* 40, no. 3 (2008): Figure 2, 395.

3.2 Energy Consumption in Building Typologies: Office and Education

Since the 1950s in the US, energy consumption in the service sector has increased from 11% to 18%. In the UK, the accumulated service energy use is at 11% (see Table 2)[40]. The service sector includes all commercial and public building types such as schools, restaurants, hotels, hospitals, and museums. Each of these types of building consumes a substantial amount of energy from building services including the HVAC system, lighting, refrigeration, food preparation, and equipment (computers, copy

[39] Ibid., 395
[40] Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information." *Energy and Buildings* 40, no. 3 (2008), 396.

machines, lighting, refrigerators, etc.). The growth of the world's population will only continue to expand the building service demands and thus energy consumption.

Table 2. "Weight of buildings energy consumption"

Final energy consumption (%)	Commercial	Residential	Total
USA	18	22	40
UK	11	28	39
EU	11	26	37
Spain	8	15	23
World	7	17	24

Data taken from 2004 Energy Information Administration (EIA), Eurostat, and BRE; 2004
Source: Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information." *Energy and Buildings* 40, no. 3 (2008): Table 3, 396.

Offices and schools account for 31% of the total energy consumption in the service sectors (see Table 3). Eighteen percent of the end use consumption comes from office building typologies. This 18% can be broken down into HVAC (48%), artificial lighting (22%), equipment (13%), domestic hot water (DHW) (4%), food preparation (1%), refrigeration (3%), and other (10%) (see Table 4). The remaining 13% schools and breaks down into HVAC (67%), artificial lighting (14%), equipment (4%), DHW (7%), food preparation (1%), and other (7%) (see Table 6). The Commercial Buildings Energy Consumption Survey (CBECS) explains building types as follows:

> buildings are classified according to principal activity, which is the primary business, commerce, or function carried on within each building. Buildings used for more than one of the activities described below are assigned to the activity occupying the most floor space. A building assigned to a particular principal activity category may be used for other activities in a portion of its space or at some time during the year.[41]

[41] U.S. Energy Information Administration. "Building Type Definitions." 2015. http://www.eia.gov/consumption/commercial/building-type-definitions.cfm (accessed April 04, 2015).

The CBECS, an ongoing project coordinated by the Energy Information Administration (EIA), is a national sample survey that collects information on the stock of US commercial buildings, including their energy-related building characteristics and energy usage data (consumption and expenditures). Commercial buildings include all buildings in which at least half of the floor space is used for a purpose that is not residential, industrial, or agricultural. By this definition, CBECS includes building types that might not traditionally be considered commercial, such as schools, hospitals, correctional institutions, and buildings used for religious worship, in addition to traditional commercial buildings such as stores, restaurants, warehouses, and office buildings.

3.2.1 Office typologies definition

CBECS defines office typologies as, "Buildings used for general office space, professional office, or administrative offices. Medical offices are included here if they do not use any type of diagnostic medical equipment (if they do, they are categorized as an outpatient health care building)."[42]

CBECS includes the following subcategories list for office typologies:

- Administrative or professional office
- Government office
- Mixed-use office
- Bank or other financial institution
- Medical office (see previous column)
- Sales office
- Contractor's office (e.g. construction, plumbing, HVAC)
- Non-profit or social services
- City hall or city center
- Religious office
- Call center

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[42] Ibid.

3.2.2 Education typologies definition

CBECS defines education typologies as buildings and classrooms on school, college, and university properties used for "academic or technical instruction."[43] CBECS includes the following list of subcategories for education typologies:

- Elementary or middle school
- High school
- College or university
- Preschool or daycare
- Adult education
- Career or vocational training
- Religious education

Perez-Lombard, Ortiz, and Pout wrote that according to the EIA's prediction of future trends in building energy consumption,

> Energy use in the built environment will grow by 34% in the next 20 years, at an average rate of 1.5%. In 2030, consumption attributed to dwellings and the non-domestic sectors will be 67% and 33% respectively (approximately)…. [T]herefore, the growth of construction will boost energy demand on the residential sector. Forecasts predict that both developed and non-developed economies will be balanced in the use of energy in dwellings by 2010. Economic, trading and population growth in emerging economies will intensify needs for education, health and other services, together with the consequential energy consumption.[44]

With an average annual increase rate of 2.8%, the service sectors in developing nations will double their energy consumption and CO_2 emissions in the next 25 years. Currently, most of the service sector's energy consumption comes from the HVAC systems in response to the demand for thermal comfort.

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[43] Ibid.
[44] Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information." *Energy and Buildings* 40, no. 3 (2008), 396.

Table 3. “Energy use in the commercial sector by building type”

Building type	USA (%)	Spain (%)	UK (%)
Retail	32	22	22
Offices	18	33	17
Hotels and Restaurants	14	30	16
School	13	4	10
Hospitals	9	11	6
Leisure	6	-	6
Others	9	-	23

Data taken from EIA, IDAE, and BRE; 2003
Source: Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information.” *Energy and Buildings* 40, no. 3 (2008): Table 5, 397.

Table 4. “Average energy use intensity by building type in USA”

Building type	kWh/m^2	Ratio
Dwellings	147	1
Retail	233	1.6
Schools	262	1.8
Offices	293	2
Hotels	316	2.1
Supermarkets	631	4.3
Hospitals	786	5.3
Restaurants	814	5.5

Data taken from EIA; 2003
Source: Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information.” *Energy and Buildings* 40, no. 3 (2008): Table 6, 397.

3.3 HVAC System

The HVAC (heating, ventilation, and air conditioning) system is one of the highest energy consumers in the building service sector for residential and non-residential building typologies. The increase of global surface temperatures over the last two decades is creating harsher climate swings, which affects living conditions in many parts of the world. The invention of the HVAC system has provided society with better living conditions, in terms of comfort level, by cooling or heating the interior space of the building. In accordance with the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and the American National Standards Institute (ANSI) Standard 90.1-2013, the purpose of HVAC systems is to provide thermal comfort and acceptable indoor air quality. According to Standard 90.1,

> HVAC system design is a sub-discipline of mechanical engineering, based on the principles of thermodynamics, fluid mechanics, and heat transfer. It is important in the design of medium to large industrial and office buildings such as skyscrapers. The three central functions of heating, ventilating, and air-conditioning are interrelated, especially with the need to provide thermal comfort and acceptable indoor air quality within reasonable installation, operation, and infiltration, and maintain pressure relationships between spaces.[45]

The increase in HVAC system demand in the service sector has caused an increase in global energy consumption. Non-domestic buildings, like office spaces, account for over 50% of the total energy consumption, following hotels, restaurants, hospitals, and schools (see Table 3).[46] The HVAC system may have improved the living conditions for many societies but it is also causing problems for the climate. The HVAC system accounts for 48% of energy consumed by end use for offices (see Table 4) and 67% for school buildings (see Table 5) in the USA.

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45 ASHRAE, "Standard 90.1-2013: Energy Standard for Buildings Except Low-Rise Residential Buildings. 2013." https://www.ashrae.org/resources--publications/bookstore/standard-90-1 (accessed April 3, 2015).

46 Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information." *Energy and Buildings* 40, no. 3 (2008), 397.

Table 5. “Energy consumption in offices by end use”

Energy end uses	USA (%)	Spain (%)	UK (%)
HVAC	48	55	52
Lighting	22	17	33
Equipment (appliances)	13	5	10
DHW	4	10	-
Food preparation	1	5	-
Refrigeration	3	5	-
Others	10	4	5

Data taken from EIA, BRE, and IDAE
Source: Perez-Lombard, Luis, Jose Ortiz, and Christine Pout. "A review on buildings energy consumption information.” *Energy and Buildings* 40, no. 3 (2008): Table 7, 397.

Table 6. “Energy consumption in school building by end use”

Energy end uses	USA (%)
HVAC	67
Lighting	14
DHW	7
Equipment	4
Food preparation	1
Others	7

Data taken from 2003 Energy Information Administration (EIA)
Source: *Millennial Net.* 2012. http://millennialnet.com/Energy-Management/Commercial/Schools.aspx (accessed April 04, 2015).

The need and demand for thermal comfort will continue to rise, and is both the cause of and exacerbated by the continuing rise in average global surface temperature, as identified in chapter 2. This growing trend in building energy consumption is predicted to continue through the end of the twenty-first century. Regrettably, HVAC has become the primary system for dealing with thermal comfort in the service sector.

Warnings about the effects of global warming and depletion of non-renewable resources have inspired some to develop more energy-efficient and high-performance buildings. To make possible a sustainable future for our planet, it is essential that we design new, better technology for energy production, limit energy consumption, and raise social awareness on the rational use of energy.

3.4 Building Envelope

A building envelope is the physical separator between the interior and exterior environment of a building. A building envelope uses exterior wall materials, such as walls, roof, and window, to mitigate the transfer of air, water, heat, light, and noise between the two environments. Buildings are the single largest energy end-use contributors to global emissions. The trend of increasing energy consumption from HVAC systems alone will result in larger CO_2 emissions, which in turn will further contribute to climate change and global warming. More energy-efficient building designs and operations are necessary in order to help lower the energy demands and reduce CO_2 emissions.

This research considers four potential mitigation measures that affect the building envelope, heat gain, lighting load, and HVAC system: exterior wall R-value, roof R-value, roof SRI, window glazing U-value, and solar heat gain coefficient (SHGC). The research examined each of the four variables based on their relatively high influence coefficients (a measure of how sensitive the building energy use would be to changes in the design variables), and on whether architects and building engineers were likely to consider them, especially in the initial conceptual design stages.[47] Different values were

[47] Wan, Kevin KW, Danny HW Li, and Joseph C Lam. "Assessment of climate change impact on building energy use and mitigation measures in subtropical climates." *Energy* 36, no. 3 (2011), 1409.

considered for each design variable representing prospective energy-efficiency measures.[48]

The R-value is a measure of the thermal resistance for a particular material or assembly of materials (*i.e.* insulation panel). R-values are the reciprocal of the thermal conductance or U-value. The term wall R-value refers to the thermal resistance of the assembly of the exterior walls and roof R-value, to the thermal resistance of the assembly of the roof.

The U-value is used to quantify overall heat flow. For a window, it expresses the total heat transfer coefficient of the system (in Btu/hr-sf-°F), and includes conductive, convective, and radiative heat transfer. The U-value of a window varies primarily based on the number of glazing panels, gases, coatings and conductivity of window frames. Finally, the SHGC is a fraction of incident solar radiation that directly and indirectly enters through a window assembly as heat gain.

3.5 Hawai'i Energy Consumption

As of 2012, the census data estimates that 1.4 million people live in the state of Hawaiʻi, 70% of which are residents of the city of Honolulu. The state of Hawaiʻi is made of up 6,422 square land miles, which makes up over half of the state's 10,932 total square miles spread over an archipelago of 130 islands that stretches over 1,500 linear miles. Energy production in Hawaiʻi is a challenge due to the islands' isolated locations and lack of local resources. The state relies heavily on imports of petroleum and coal for power, although recent initiatives have increased the use of renewable resources. In short, powering a population of this scale in such a geographical location requires substantial energy supplies and infrastructure. According to the EIA, of the 94% of electricity used by the state's residents, a little over 73% is generated from burning oil since Hawaiʻi has

[48] Ibid.

no means of burning fossil fuel. Figure 8 illustrates the breakdown of energy consumption in Hawaiʻi by sector.

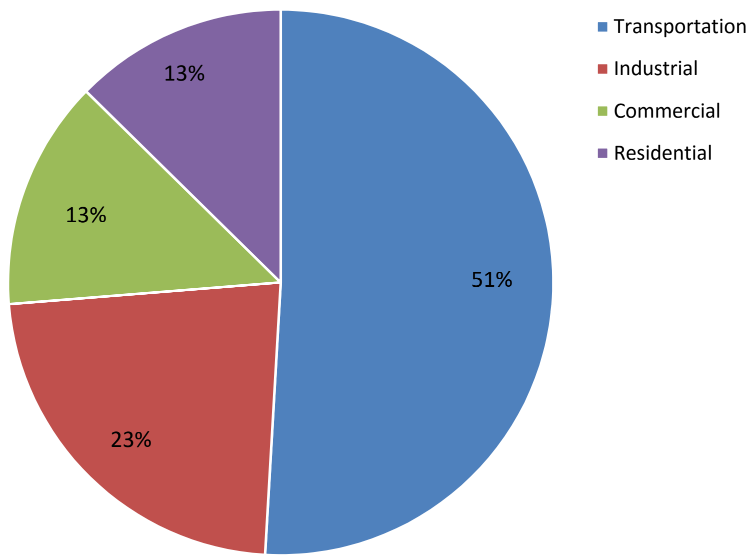

Figure 8. “Hawaii energy consumption by end-use sector 2012”
Source: US Energy Information Administration. “Building Type Definitions.” 2015. http://www.eia.gov/consumption/commercial/building-type-definitions.cfm (accessed April 04, 2015).

Chapter 4: Significance of Weather Data

4.1 What is a Typical Meteorological Year (TMY) Weather Data

An hourly weather file is a prerequisite for using building energy simulation (BES) software to estimate the impact of current climate conditions on building performance. Traditionally, weather files for BES programs have been provided as hourly datasets in a variety of formats depending on country and origin of the files. One of the most available hourly weather files is the Typical Meteorological Year (TMY) file.[49] The TMY file is a collation of selected hourly weather data for a specific location, generated from a data bank of 30 years, if available.[50] These data sets are widely used by architects and others for building performance simulation (BPS) programs. BPS programs use computer simulation to model the various energy loads and air flow within a building in order to predict one or several performance aspects of a building. An architect may also use the weather file to verify the sustainability of the building design form and skin in relation to the current climate environment.

The TMY files are data sets of hourly values of solar radiation and meteorological elements compiled for one-year periods. A TMY file is composed of twelve typical meteorological months (January through December) that combine, essentially without modification, to form a single year with a serially complete data record for primary measurements. These monthly data sets contain actual time-series meteorological measurements and modeled solar values.[51]

Sandia National Laboratories produced the first TMY data set for the US in 1978 using long-term weather and solar data from the 1952–1975 SOLMET/ERSATZ

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[49] Jentsch, Mark F, AbuBakr S Bahaj, and Patrick AB James. "Climate change future proofing of buildings - Generation and assessment of building simulation weather files." *Energy and Buildings* 40, no. 12 (2008), 2150.
[50] Wilcox, Stephen, and William Marion. *Users Manual for TMY3 Data Sets* (Golden, CO: National Renewable Energy Laboratory, 2008), 1.
[51] Ibid.

databases for 248 locations. The National Renewable Energy Laboratory (NREL) updated the TMY data in 1994 using data from the previous 30 years (1961–1990) provided by the National Solar Radiation Data Base (NSRDB). In 2007, NREL released the latest TMY3 data set with a 15-year updated NSRDB (1991–2005). Thus, the TMY3 is produced using input data from 1976 to 2005, from the 1961 to 1990 NSRDB, and from the 1991 to 2005 NSRDB update.[52] The TMY weather files are free public downloadable files available via the World Wide Web at the US Department of Energy (DOE). There are three versions of the TMY weather files that can be downloaded. The DOE, on their website, describe the TMY files as follows:

> **Typical Meteorological Year (TMY)**
>
> Data for 230 locations in the USA plus four locations in Cuba, Marshall Islands, Palau, and Puerto Rico, derived from a 1948-1980 period of record. Many of the locations in the TMY data set were subsequently updated by the TMY2.
>
> Similar to the TMY2, the TMY are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories….
>
> **Typical Meteorological Year 2 (TMY2)**
>
> The TMY2 are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories….
>
> TMY3 files have somewhat replaced TMY2 files but all TMY2 files are available for download from the website.
>
> **Typical Meteorological Year 3 (TMY3)**
>
> Data for 1020 locations in the USA including Guam, Puerto Rico, and US Virgin Islands, derived from a 1991-2005 period of record….
>
> The TMY3s are data sets of hourly values of solar radiation and meteorological elements for a single year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to

[52] Ibid.

> facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories.[53]

The DOE recommends that users acquire the TMY3 weather files for BPS programs because these contain the most recent recorded data available. The TMY3 weather files contain the data for 1020 locations, compared to 239 locations for the TMY2 weather files. A study done by Stephen EC Pretlove and Tadj Oreszczyn in 1998, discussed in greater detail in the following section, examines and establishes the importance of using the most recent recorded data available for building design.

4.2 Case Study: The impact of Weather Files on Building Energy Simulation

According to Pretlove and Oreszczyn in, “Climate change: impact on the environmental design of buildings,” while buildings are usually built for a singular climate, they are also built to last no more than one hundred years. During this time period, however, the climate may change dramatically. To exacerbate the problem, most climate data in the Thames Valley region in England, where the study was conducted, is 30 years old. The study determined the specific impacts of temperature and solar radiation on energy use for one office building in the Thames Valley. The methodology was to analyze the actual climate data gathered from the nearby weather stations and compare them to existing weather files from previous years. The actual climate data collected for this study includes degree-day data for the Thames Valley from 1976 to 1995, average monthly temperatures for Heathrow from 1981 to 1996, and average monthly solar radiation data for Bracknell from 1981 to 1995.[54]

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[53] US Department of Energy. February 12, 2015. http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_sources.cfm (accessed April 05, 2015).

[54] Pretlove, Stephen EC, and Tadj Oreszczyn. "Climate change: impact on the environmental design of buildings." *Building Service Engineering Research and Technology* 19, no. 1 (1998), 59.

The analysis shows substantial changes between actual climate data and existing weather data. The initial analysis of collected data involved identifying and quantifying trends over the past two decades. Figure 9 shows that the data displayed an 11% decrease in average annual monthly degree-days over the last 20 years. For Heathrow, over the last 15 years, the average annual temperatures increased by 0.6°C, representing a 6% increase. Figure 10 shows the collected average monthly temperature data together with similar moving average and linear trend lines. Figure 11 shows the results from Bracknell weather station, which displayed an increase of 3% in the average annual solar radiations over the last 15 years.[55] The results from the actual climate data in the Thames Valley are expected to show increases in temperature and solar radiation because of global warming and climate change.

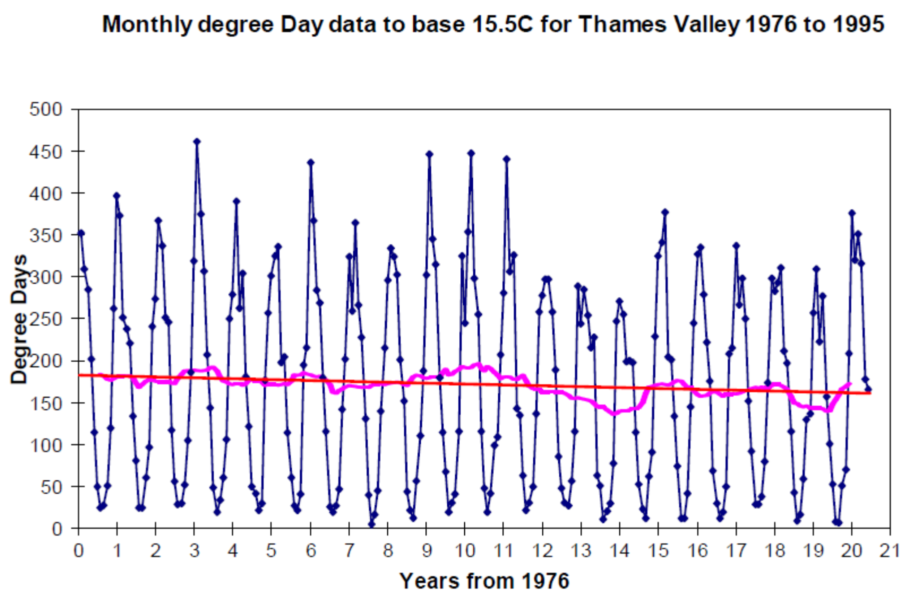

Figure 9. This figure indicates the collected degree-day data to a base temperature of 15.5°C for the Thames Valley region for the last 20 years.
Source: Pretlove, Stephen EC, and Tadj Oreszczyn. "Climate change: impact on the environmental design of buildings." *Building Service Engineering Research and Technology* 19, no. 1 (1998): Figure 1, 66.

[55] Ibid., 60.

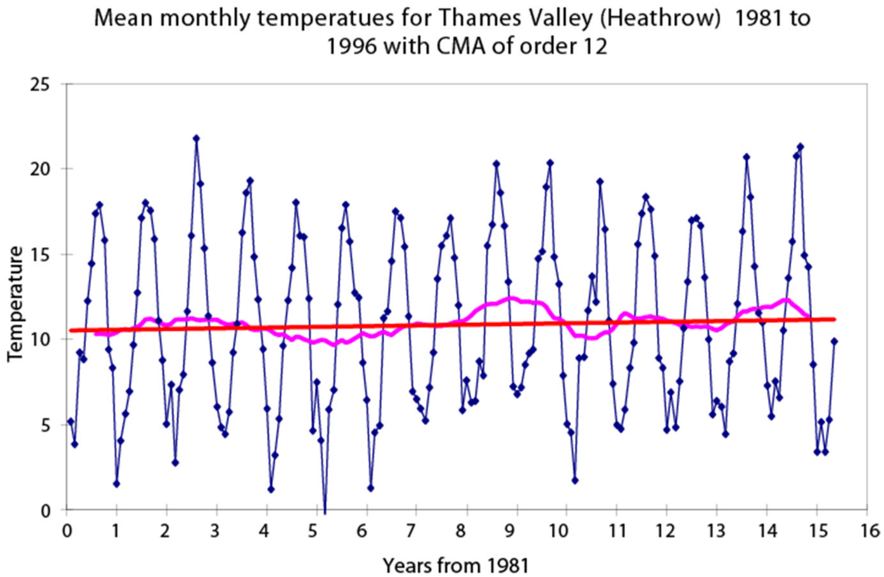

Figure 10. The mean annual temperatures measured at Heathrow over the last 15 years have increased by 0.6°C.
Source: Pretlove, Stephen EC, and Tadj Oreszczyn. "Climate change: impact on the environmental design of buildings." *Building Service Engineering Research and Technology* 19, no. 1 (1998): Figure 2, 66.

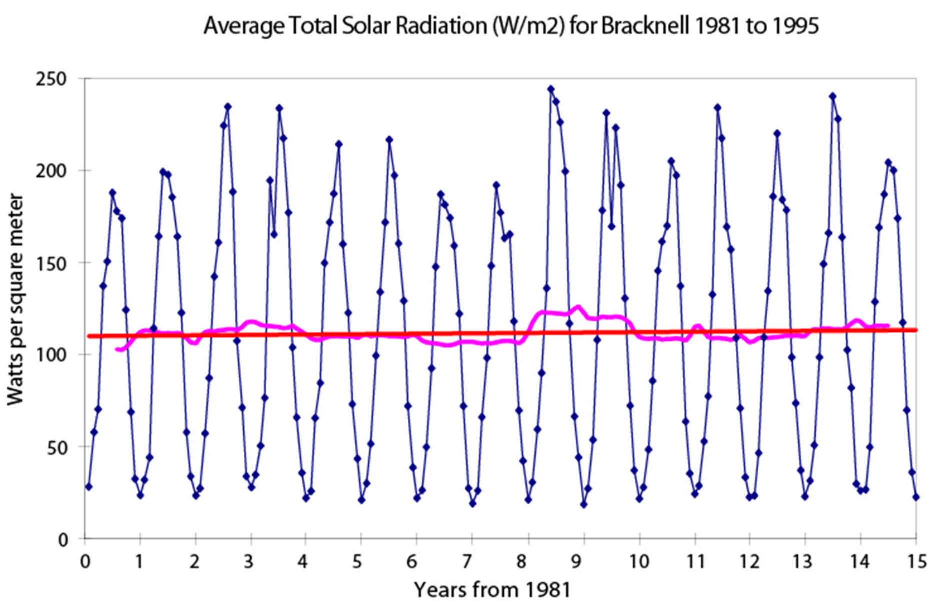

Figure 11. The average annual solar radiation has increased by 3% during the last 15 years.
Source: Pretlove, Stephen EC, and Tadj Oreszczyn. "Climate change: impact on the environmental design of buildings." *Building Service Engineering Research and Technology* 19, no. 1 (1998): Figure 3, 67.

Pretlove and Oreszczyn compared the results of the actual climate data obtained from the weather stations with the design calculations of CIBSE Building Energy Code, the Government SAP energy rating, and the BREDEM-8 monthly energy rating. Each of these three design calculations applied the actual climate data to the standard heated and naturally-ventilated office-building model for the purpose of identifying the accuracy of the weather data between the actual climate data and the design method data.[56]

Surprisingly, all three of the design calculations, using weather files, overestimated the climate effects of the office building. The CIBSE Building Energy Code overestimated the thermal demand of the building by 8%. The Government SAP rating overestimated the space-heating requirement by 17%. Finally, the BREDEM-8 overestimated the space-heating requirement by 7%.

We can conclude that the weather files created by CIBSE, SAP, and BREDEM-8 overestimated the climate change by comparing the results to the actual climate data from the nearby weather stations. It is possible the weather files are outdated because of the rapid change in climate conditions over the past two decades. In essence, a weather file is a collation of selected weather data, generated from a data bank of 30 years duration. Pretlove and Oreszczyn recommend, "Climate data used for building design calculations should be regularly reviewed and updated otherwise its use may result in buildings not suitable for the next millennium."[57] In this case, the use of accurate and updated weather files is important for specific predictions of energy use on the building. In contrast, the readily available weather files provided by the DOE are acceptable for building analysis because they emulate the average single weather year from an up-to-date dataset of 30 years duration. Pretlove and Oreszczyn also propose that data should represent the most recent available weather files for most accurate results.

Unfortunately, the use of present-day weather files for BPS programs is not suited for assessing the potential impacts of the changing climate on a building; it is only

[56] Ibid., 60.
[57] Ibid., 63.

capable of predicting the building performance for the first five years or so. Within this predicted period, climate change will not be significant enough to affect the building's performance, but very likely will change significantly during the 50 to 100 years of the building's possible life. The use of weather files should reflect the potential impacts of changing climate well into the future.

To allow simulations of building behavior under projected conditions, techniques have been developed that adjust current TMY3 weather files to reflect climate change scenarios predicted by the 2007 IPCC AR4, a method proposed by Stephen Belcher of the Met office Hadley Centre to generate future weather files to reflect climate change for worldwide locations use in building performance simulation (BPS) software.

Chapter 5: Future Weather Files

5.1 Introduction

Based on observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level, as discussed in chapter 2, we can conclude that global warming and climate change do exist. The effects of climate change will last through the end of this century, according to many climate scientists, no matter how we choose to act now. Even if the CO_2 emissions are seriously reduced, these scientists predict that emissions from the twentieth century will still affect the climate for many decades. Thus, as we move into the future, we can assume that global surface temperatures will likely continue to rise and thus continue to affect the performances of buildings. Even with the use of building energy simulation (BES) programs, the predictions are still limited because we are mainly using present-day weather files. The use of present-day weather files is no longer suited for assessing the impacts of climate change in the future. For BES programs, we must focus on creating future weather files that reflect and predict the changing climate.

In order to generate such future weather files, an appropriate method needs to be established. Stephen Belcher, a professor of meteorology and head of the Met office Hadley Centre, developed a method to generate future weather files using present-day existing weather files introduced and now referred to as the "morphing" technique. Mark Jentsch, AbuBakr Bahaj, and Patrick James then used this technique in the publicly available tool CCWorldWeatherGen (see section 5.4) to produce weather prediction files for the years 2020, 2050, and 2080.[58] According to Belcher and his coauthors, Jacob Hacker and Diane Powell, this method of simulated future weather files has two practical advantages: first, the baseline climate is proven reliable because it is the climate

[58] Barnaby, Charles S, and Drury B Crawley. *Building Performance Simulation for Design and Operation.* Edited by Jan L.M. Hensen and Roberto Lamberts (Abingdon, Oxon: Spon Press, 2011), 50.

condition for the present-day weather files; and second, the resulting weather sequence is likely to be meteorologically consistent with the general circulation models (GCM).[59]

5.1.1. Algorithms for morphing the weather data

The simulated future weather files involve three generic operations: (1) a shift, (2) a linear stretch (scaling factor), and (3) a shift and a stretch. Belcher, Hacker, and Powell specified the following algorithms for morphing:

1. A shift by Δx_m is applied to the present-day climate variable x_0 by

$$x = x_0 + \Delta x_m$$

For each month *m*, where Δx_m is the absolute change in the monthly mean value of the variable for the month *m*. The new monthly mean of the variable is then $(x)_m = (x_0)_m + \Delta x_m$, and hence the climate has been shifted from baseline by Δx_m. The monthly variance of the variable is unchanged.

2. A stretch of α_m is applied by

$$x = \alpha_m x_0$$

Where α_m is the fractional change in the monthly-mean value for month *m*. This method changes the monthly mean to $(x)_m = \alpha_m (x_0)_m$, confirming that the desired mapping has been made. The variance is also changed and becomes $(\sigma^2)_m = \alpha^2{}_m (\sigma^2{}_0)_m$.

3. A combination of shift and stretch is obtained by

$$\begin{aligned} x &= x_0 + \Delta x_m + \alpha_m \, x \, (x_0 - (x_0)_m) \\ &= (x_0)_m + \Delta x_m + (1 + \alpha_m)\,(x_0 - (x_0)_m) \end{aligned}$$

The new monthly mean is then $(x)_m = (x_0)_m + \Delta x_m$ and the new monthly variance is $(\sigma^2)_m = \alpha^2{}_m (\sigma^2{}_0)_m$.[60]

They go on to explain,

A shift is used when the climate change scenario lists an absolute change to the mean. A stretch is used when there is a change to the mean or variance quoted as a percentage or fractional change rather than an absolute increment or when the variable can be switched off altogether, as in for example, solar irradiance, which is zero at night. A combination of a shift and a stretch is used when both the mean

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[59] Belcher, Stephen E, Jacob N Hacker, and Dianne S Powell. "Constructing design weather data for future climates." *Building Services Engineering Research and Technology* 26, no.1 (2005), 50.
[60] Ibid.

> and the variance need to be changed, for example when changing temperature to reflect changes in both the daily mean and the maximum and minimum daily temperatures.[61]

Further details of the simulated future weather files algorithms can be found in Belcher, Hacker, and Powell's journal article, "Construction design weather data for future climates."

The first step in making a simulated future weather file is to make projections of GHG emissions and atmospheric concentrations. These projections are based on four emissions scenarios (A1, A2, B1, and B2) taken from the 2007 IPCC SRES.[62] These four scenarios represent a set of possible future trends, ranging from an unsustainable future with high-intensive GHG emissions to a sustainable one with low GHG emissions.

5.2 Special Report on Emissions Scenarios (SRES)

The 2007 IPCC SRES focuses on future climate projections based on the amounts of GHG emissions from four possible future scenarios. These four possible future scenarios (A1, A2, B1, and B2) explore alternative development pathways, covering a range of demographic, social-economic, and technologies driven forces that result in GHG emissions (see figure 10). Under the 2007 IPCC SRES report, future projections show the global surface temperature will increase by a range of 1.1°C to 6.4°C by the end of the twenty-first century under the highest GHG emissions scenarios.[63]

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[61] Ibid.

[62] Ibid., 54.

[63] Nakicenovic, Nebojsa, and Rob Swart, et al., eds. "Summary for Policymakers: Atmosphere and Surface," In IPCC, 2000: *Climate Change 2000: Special Report Emissions Scenarios. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2000), 3.

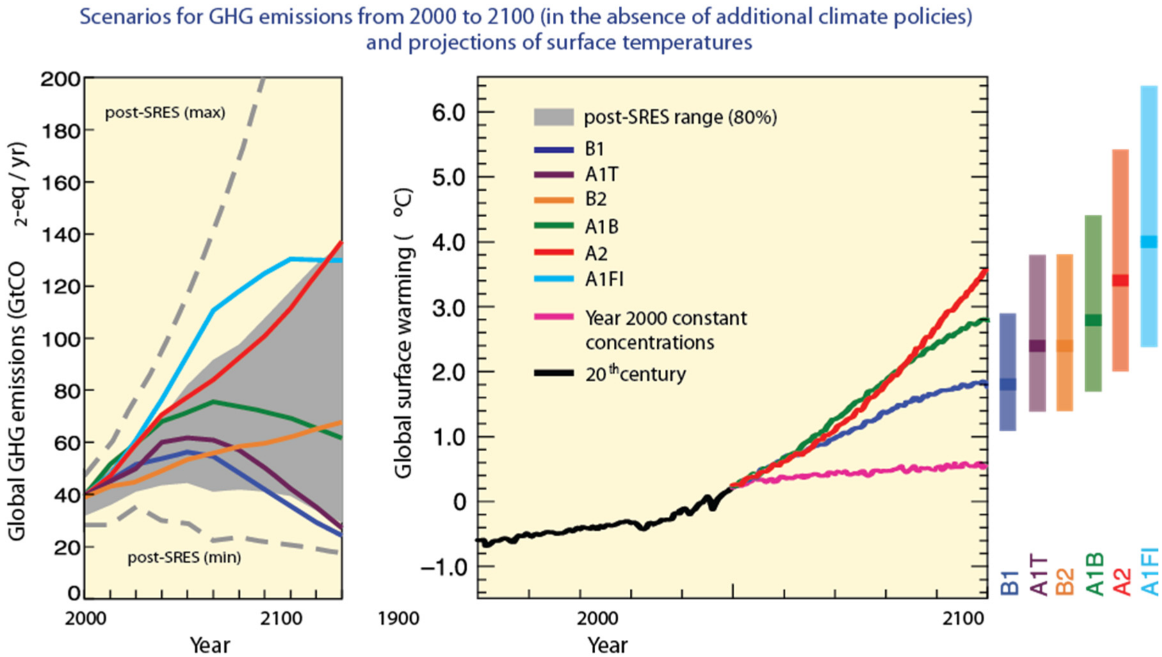

Figure 12. Global averages of surface warming for six different scenarios predicted by the SRES 2000 report.
Source: Pachauri, Rajendra K, and Andy Reisinger, et al., eds. "Synthesis Report," in IPCC, 2007: *Climate Change 2007: Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland, 2007): Figure SPM.5, 7.

The SRES future projections are widely used in many assessments of future climate change. Each of these scenarios describes the relationships between the forces driving GHG and aerosol emissions and their evolution through the twenty-first century.

The SRES "Summary for Policymakers: Emissions Scenarios," describes each storyline in more detail:

> The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis:

fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).[64]

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines.[65]

The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.[66]

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with a global population that increases continuously at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on the local and regional levels.[67]

Under the SRES climate change projection, an increase of 0.2°C per decade is expected for each SRES scenario. Even if GHG emissions were to reduce, a further warming of about 0.1°C increase per decade would still be expected (see Table 7).

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[64] Ibid., 4.
[65] Ibid., 5
[66] Ibid., 5.
[67] Ibid., 5.

Table 7. “Projected global average surface warming and sea level rise at the end of the 21st century.”

	Temperature Change (°C at 2090-2099 relative to 1980-1999)		Sea level rise (°C at 2090-2099 relative to 1980-1999) a, d (m at 2090-2099 relative to 1980-1999)
Case	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentration	0.6	0.3 – 0.9	Not available
B1 Scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T Scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 Scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B Scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 Scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI Scenario	4.0	2.4 – 6.4	0.26 – 0.59

Source: Pachauri, Rajendra K, and Andy Reisinger, et al., eds.. IPCC, 2007: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland, 2007): Table 3.1, 45.

5.3 Foresight Scenarios (UKCIP)

According to Roaf, Crichton, and Nicol, the UK Foresight Program, the Royal Commission on Environmental Pollution, and the UK Climate Impacts Program (UKCIP) are the most influential scenarios programs set in Britain. The UK Foresight Program draws on the expertise of thousands of leading people from businesses, universities, the government, and other institutions. The purpose of the program, which began in 1993, is to identify technical opportunities and social drivers in our changing world to help shape research priorities, both in the private and public sectors. Eventually, it became a standard practice for the British government to require organizations asking for funding to identify how their research will fit into the Foresight Scenarios Program.[68]

The scenarios are important in identifying a range of possible social and economic futures based on certain decisions that could be taken today. The UK Cabinet Office makes use of this methodology in formulating strategies and policies, according to Roaf, Crichton, and Nicol. These scenarios have been widely used as the basis for other complex scenarios, like the UK Climate Impact Projection 2002 (UKCIP02), which created projected future scenarios for the twenty-first century.[69]

5.3.1 The UKCIP02 scenarios

The UK Climate Impact Projection 2002 (UKCIP02) scenarios represent an advanced description of future UK climates based on the scenarios published by UKCIP in 1998. The new projections based on the integration of the new global emissions scenarios are published in the 2000 IPCC AR3 in the SRES climate models.[70] The

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[68] Roaf, Sue, David Crichton, and Fergus Nicol. *Adapting Buildings and Cities for Climate Change: A 21st century survival guide* (Amsterdam: Architectural Press, 2005), 66.
[69] Ibid.
[70] Hulme, Mike, et al. 2002: *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report.* Norwich, UK: Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia (Norwich, UK, 2002), iv.

UKCIP02 is a series of climate modeling experiments completed by the Hadley Centre using its most recently developed models for the UK climate, covering four alternative future climates based on social and economic scenarios:

- High emissions (A1)
- Medium high emissions (A2)
- Medium low emissions (B1)
- Low emissions (B2)

Table 8. "Changes in global temperature (°C) and atmospheric carbon dioxide concentration (CO_2) for the 2080 period (2071-2100 average) on the four UKCIP projected scenarios."

SRES emissions scenarios	UKCIP02 climate change scenario	Increase in global temperature (°C)	Atmospheric CO_2 concentration (ppm)
B1	Low Emissions	2.0	525
B2	Med Low Emissions	2.3	562
A2	Med High Emissions	3.3	715
A1FI	High Emissions	3.9	810

Note. The atmospheric CO_2 concentration in 2001 was about 370 ppm.
Source: Roaf, Sue, David Crichton, and Fergus Nicol. *Adapting Buildings and Cities for Climate Change: A 21st century survival guide.* Amsterdam: Architectural Press, 2005: 69.

Table 8 represents the results of the 2002 UKCIP Scientific Report on future predictions of climate changes in Britain. The UKCIP scenarios provide detailed information on future climate predictions in various geographical locations in the UK. The findings in this report initiate a substantial amount of scientific research and thousands of simulation runs in hope of predicting future climate changes.

Many climate scientists in the world acknowledge the certainty of climate change up to 2040. Most agree that, no matter what our actions are starting from this point in time, the amount of atmospheric CO_2 concentration in 2040 will still reflect our past contribution of CO_2 emissions. This claim is supported by Roaf, Crichton, and Nicol, who write, “Many of the future changes that will happen over the next 30-40 years have already been determined by historic emissions and because of the inertia in the climate system”.[71] Belcher, Hacker, and Powell also agree that results from the atmospheric CO_2 concentrations up to 2040 will likely be largely governed by past emissions because the lifespan of CO_2 in the atmosphere is about 100 years.[72] This explains why the projected climates under the four emissions scenarios do not diverge significantly until 2040. It is predicted that many more changes in the climate will take place in the latter half of this century. This will have huge impacts on every person, building, society, and country on the planet.

UKCIP02 scenarios suggest that by 2080, the atmospheric CO_2 concentrations may be between 525 parts per million (ppm) and 810 ppm (see Table 8). We will therefore have to adapt to some degree of climate change, whether future emissions are reduced or not. This dissertation explores the use of the future weather files developed by Belcher, Hacker, and Powell in 2005 and Jentsch, Bahaj, and James in 2008 for BES programs to assess and mitigate the impacts of climate change for the future performance of buildings.

5.4 Future Weather Data Creation Software

5.4.1 Meteonorm

Meteonorm is a database that provides temperature, solar radiation, and other weather data from over 8,000 weather stations worldwide as well as five satellites. It offers current information and prediction scenarios. The database is widely used by

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[71] Roaf, Sue, David Crichton, and Fergus Nicol. *Adapting Buildings and Cities for Climate Change: A 21st century survival guide* (Amsterdam: Architectural Press, 2005), 68.
[72] Belcher, Stephen E, Jacob N Hacker, and Dianne S Powell. "Constructing design weather data for future climates." *Building Services Engineering Research and Technology* 26, no. 1 (2005), 54.

architects and planners for building design. The software is based on more than 30 years of experience in the development of meteorological databases for BES software. It provides worldwide monthly climatological means for the following eight parameters:[73]

- Global irradiance
- Ambient air temperature
- Humidity
- Precipitation
- Days with precipitation
- Wind speed
- Wind direction
- Sunshine duration

Although Meteonorm weather files are not available for free, as are DOE weather files, the program can be purchased online for generating both present-day and future weather files. Meteonorm uses projected future scenarios provided by the 2007 IPCC AR4 to generate its future weather files. Three different scenarios are available: A2 (second highest emissions), A1B (mid emissions), and B1 (low emissions).[74] Meteonorm uses stochastic weather generators to create these scenarios. According to Belcher, Hacker, and Powell, a stochastic weather generator is a system,

> where synthetic weather time series are generated using empirically 'derived statistics.' Whilst this method is computationally cheap, it does require large data sets to train the model to give appropriate statistics and fix unknown model coefficients, and the weather series it produces may not always be meteorologically consistent.[75]

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[73] Meteotest. "Features: List of all Meteonorm Features." n.d. http://meteonorm.com/en/features (accessed May 2, 2015).
[74] Remund, Jan, Stefan Muller, Stefan Kunz, Barbara Huguenin-Landl, Christian Studer, Daniel Klauser, and Christoph Schilter. *Meteonorm Global Meteorological Database: Handbook Part 1: Software* (Switzerland, September, 2012), 45
[75] Belcher, Stephen E, Jacob N Hacker, and Dianne S Powell. "Constructing design weather data for future climates." *Building Services Engineering Research and Technology* 26, no.1 (2005), 50.

With Meteonorm, temperature, humidity, wind speed, and precipitation data is available for the periods ranging from 1961 to 1990 and 2000 to 2009; and irradiance data is available for the periods ranging from 1981 to 1990 and 1991 to 2010. In order to obtain a TMY (typical metrological year), hourly values of all parameters are derived from a stochastic model from local weather stations' available data.[76] The TMY is based on the latest period data Meteonorm gathered for any desired location. Despite all of this data, Meteonorm's future weather files still contain areas of uncertainties due to our weaknesses in fully understanding climate systems and the unknowns of future GHG emissions. Jan Remund and Stefan Muller noted that the Meteonorm global irradiance data uncertainty error rate ranges from 2 to 10 percent.[77]

5.4.2 CCWorldWeatherGen

The Climate Change World Weather file Generator (CCWorldWeatherGen) tool uses the Hadley Centre Coupled Model, Version 3 (HadCM3) of the Atmosphere-Ocean General Circulation Models (AOGCMs) datasets. The AOGCMs datasets were created by the IPCC Working Group I to predict future climate changes using the physics of atmospheric motion.[78] The AOGCMs were used in many of the climate models presented in the 2007 IPCC AR4 report, which states, "The AOGCMs provide credible quantitative estimates of future climate change."[79] There are four main AOGCMs being used for predicting future climate changes now, but for the purpose of this research, we will only focus on the HadCM3 model.

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[76] Bellia, Laura, Alessia Pedace, and Francesca Fragliasso. "The role of weather data files in Climate-based Daylight Modeling." *Solar Energy* 112 (2014), 173.

[77] Remund, Jan, and Stefan C Muller. "Solar Radiation and Uncertainity Information of Meteonorm 7." In *Proceedings of 26th European Photovoltaic Solar Energy Conference and Exhibition* (2011), 4388.

[78] Hensen, Jan LM and Roberto Lamberts, eds. *Building Performance Simulation for Design and Operation* (Abingdon, Oxon: Spon Press, 2011), 50.

[79] Solomon, Susan, et al., eds. "2007: Climate Models and Their Evaluation." In IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (New York: Cambridge University Press, 2007), 591.

Combining the HadCM3 model with the CCWorldWeatherGen will allow the creation of future weather files for worldwide locations for use in building energy simulation (BES) programs. It uses the 2007 IPCC model summary data of the HadCM3 model, which is available from the IPCC Data Distribution Centre (DDC). The tool, Microsoft® Excel-based, transforms present-day EnergyPlus/Typical Meteorological Year 3 (EPW/TMY3) weather files into climate change EPW/TMY3 weather files, which are compatible with the majority of building energy simulation (BES) software.[80]

The CCWorldWeatherGen tool is based on the work of the Sustainable Energy Research Group (SERG) on climate change transformation to simulate future weather files that reflect the changing climate conditions. Using the same "morphing" technique developed by Belcher, Hacker, and Powell for simulating future weather files. The CCWorldWeatherGen tool is able to generate future weather files that encapsulate the average weather conditions of cultural climate scenarios, while preserving realistic weather sequences. In essence, the generated future weather files hold the potential of aiding building designers in preparation for future changing climate scenarios.[81]

As discussed, the use of present-day weather files has become ineffective for use in BES programs to assess the potential impacts of climate change. According to Jentsch, Bahaj, and James, "Weather data files used by energy performance simulation programs are derived of historic weather data and therefore at best can be used to predict performance under 'present-day' climate conditions. They are clearly not appropriate for future building performance assessment".[82] Performance assessment and prediction tools such as BES software are becoming necessary for the planning stages of building design.

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[80] Sustainable Energy Research Group. University of Southampton. "Climate Change World Weather File Generator for World-Wide Weather Data – CCWorldWeatherGen." October 2013. http://www.energy.soton.ac.uk/ccworldweathergen/ (accessed March 25, 2015).
[81] Ibid.
[82] Jentsch, Mark F, AbuBakr S Bahaj, and Patrick AB James. "Climate change future proofing for buildings - Generation and assessment of building simulation weather files." *Energy and Buildings* 40, no. 12 (2008), 2149.

BES software that uses future weather files can deliver valuable information on the potential impacts of climate change on building design.

The integration of the HadCM3 model into the EnergyPlus Weather/Typical Meteorological year 3 (EPW/TMY3) file formats allows the creation of future weather files for worldwide locations ready for use in BES programs. Unfortunately, the current building industry only has access to the present-day weather files from the USDOE. Despite significant interest, there is evidence that future weather files are often not readily available. Jentsch, Bahaj, and James note this lack of availability of approved climate change weather files in their 2008 article, "Energy and Buildings."[83] Peter Jones and Philip Thornton, in their article, "Agricultural Systems," also note that the lack of availability of weather files is a serious impediment to undertaking climatic modeling needed to assess the impacts of the changing climate.[84] The lack of available future weather files is partly due to the difficulty of acquiring the data and method of creating a predicted future weather files.

Unfortunately, the difficulties of obtaining future weather files restrict many researchers and professionals seeking to study and understand the impacts of changing climate on building performances. It was decided, in order to give both the research and professional communities access to climate change assessments, a climate change world weather file generator tool should be made publicly available where users would be able generate their own future weather files.[85] A part of this dissertation research is thus dedicated to informing researchers and professionals on how to create a future weather file using the free software, CCWorldWeatherGen, which uses various climate change models from the 2007 IPCC AR4 to predict and interpolate future climates based on global warming trends. This would allow designers to import weather files with TMY

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[83] Ibid., 2150.
[84] Jones, Peter G, and Philip K Thornton. "Generating downscaled weather data from a suite of climate models for agricultural modelling applications." *Agricultural Systems* 114 (2012), 1.
[85] Jentsch, Mark F, AbuBakr S Bahaj, and Patrick AB James. "Climate change future proofing of buildings - Generation and assessment of building simulation weather files." *Energy and Buildings* 40, no. 12 (2008), 2158.

data and export climate change future weather files for the years 2020, 2050, and 2080 that could be used by any BES software for energy assessment.

5.5 Case Study: Certainty of Future Weather Files

"A Comparison of future weather created from morphed observed weather and created by a weather generator," is a study published in the journal, *Building and Environment*, conducted by M Eames, Tristan Kershaw, and David Coley to determine the accuracy of future weather files. The authors proposed using two different methods to produce future weather files for comparison with the actual observed weather dataset using the recently released dataset provided by the UK Climate projection 2009 (UKCP09) mentioned in section 5.3, to produce future weather files.

The UKCP09 climate data produced in 2009 was funded by a number of agencies led by Dafra. It is based on the previous version, UKCIP02, along with many sophisticated scientific methods provided by the Met office with input from over 30 contributing organizations.[86] Compared to the 2002 version, UKCP09 projections are able to capture uncertainty in future climate models more accurately and produce better projections of future emissions. Details of the climate model's uncertainties can be found in the UKCP09 science report. Briefly, uncertainties in projections of future climate change are due to three principal causes: natural climate variability, both internal and external; uncertainties in future emissions of greenhouse gases (which depend on society's choices); and uncertainties in how the climate system will respond to these emission.[87]

The current future weather files being distributed in the UK by the Chartered Institution of Building Services Engineers (CIBSE) are created using the same technique

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[86] UK Climate Projections. "About UKCP09." December 04, 2014. http://ukclimateprojections.metoffice.gov.uk/21684 (accessed April 12, 2015).
[87] Murphy, James, et al. *2009: UK Climate Projections science report: Climate change projections* (Exeter: Met Office Hadley Centre, 2010), 20.

developed by Belcher, Hacker, and Powell back in 2005. This technique uses the present-day observed weather files to transform the dataset associated with the changing climate.[88] Eames, Kershaw, and Coley wanted to study the accuracy of both the statistical weather generator developed by Jentsch, Bahaj, and James in 2008 and the transformation of the historical observations weather technique developed by Belcher, Hacker, and Powell in 2005.

5.5.1 The statistical weather generator

The weather generator uses the stochastic method to create future weather files. The stochastic method creates statistically plausible synthetic weather on an hourly or daily basis with climate projections. Belcher, Hacker, and Powell noted that the weather series the stochastic method produces might not always be meteorologically consistent. Instead, Belcher and his co-authors recommended the use of time series adjustments that use present-day observed weather files to predict future climate conditions.[89] The weather generator process starts from a well-established statistical relationship between observed climatic variables, in this case the TMY3 weather files. The projections are then used to transform these present-day observed TMY3 weather files into future TMY3 weather files.[90]

The weather generator outputs nine variables: daily precipitation, maximum temperature, minimum temperature, sunshine fraction, vapor pressure, relative humidity, direct radiation, diffuse radiation, and potential evapotranspiration. The nine outputs are compared to the hourly observations dataset from the same period (1961-1990).[91]

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[88] Eames, M, Tristan Kershaw, and David Coley. "A comparison of future weather created from morphed observed weather and created by a weather generator." *Building and Environment* 56 (2012), 252.
[89] Belcher, Stephen E, Jacob N Hacker, and Dianne S Powell. "Constructing design weather data for future climates." *Building Services Engineering Research and Technology* 26, no.1 (2005), 50.
[90] Eames, M, Tristan Kershaw, and David Coley. "A comparison of future weather created from morphed observed weather and created by a weather generator." *Building and Environment* 56 (2012), 253.
[91] Ibid., 253.

Figure 13 shows the comparison of the observed and generated mean temperature, maximum temperature, minimum temperature, and wind speed for the location of Plymouth. The result shows the observed and generated weather files to be very similar, which means a weather generator is able to simulate accurate temperature changes.

Figure 14 shows a comparison of observed and generated average sunshine duration and global irradiation for the locations of Camborne, London, and Belfast. The graph shows what seems to be a small percentage of overestimation for cloud coverage. However, the weather generator was able to predict the average monthly global horizontal irradiation accurately, with a 1% margin of error.[92] The overestimated cloud coverage seems to have no effects on the results of global irradiation. As demonstrated from the two studies, the use of a weather generator can be justified for producing future weather files for BES software.

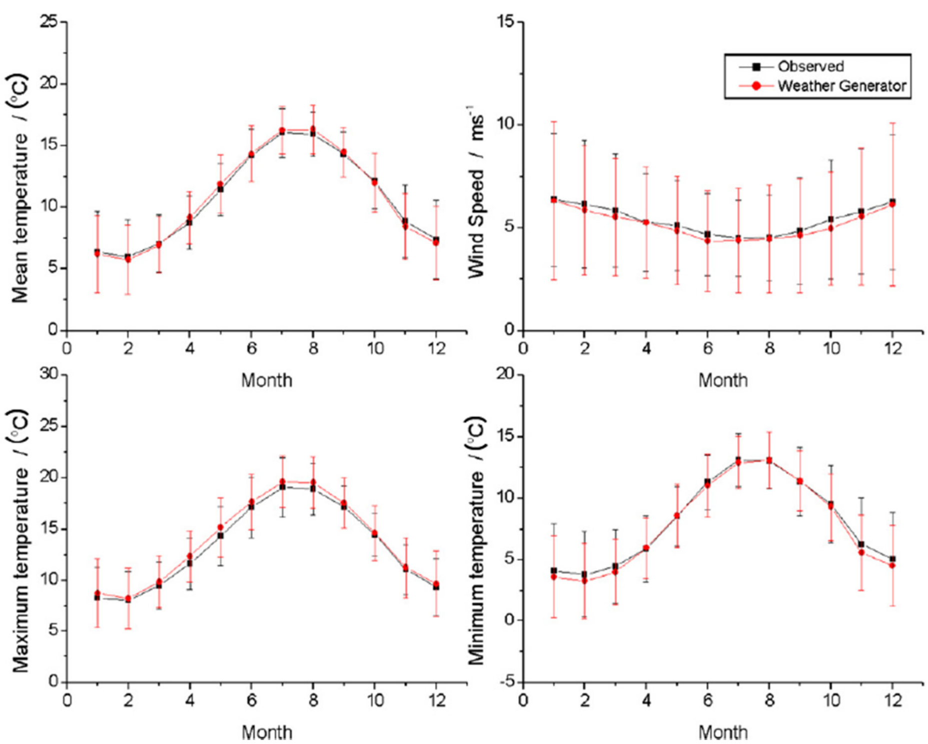

Figure 13. "Comparison between the UKCP09 weather generator and hourly observations dataset for Plymouth."
Source: Eames, M, Tristan Kershaw, and David Coley. "A comparison of future weather created from morphed observed weather and created by a weather generator." *Building and Environment* 56 (2012): Figure 1, 254.

[92] Ibid., 255.

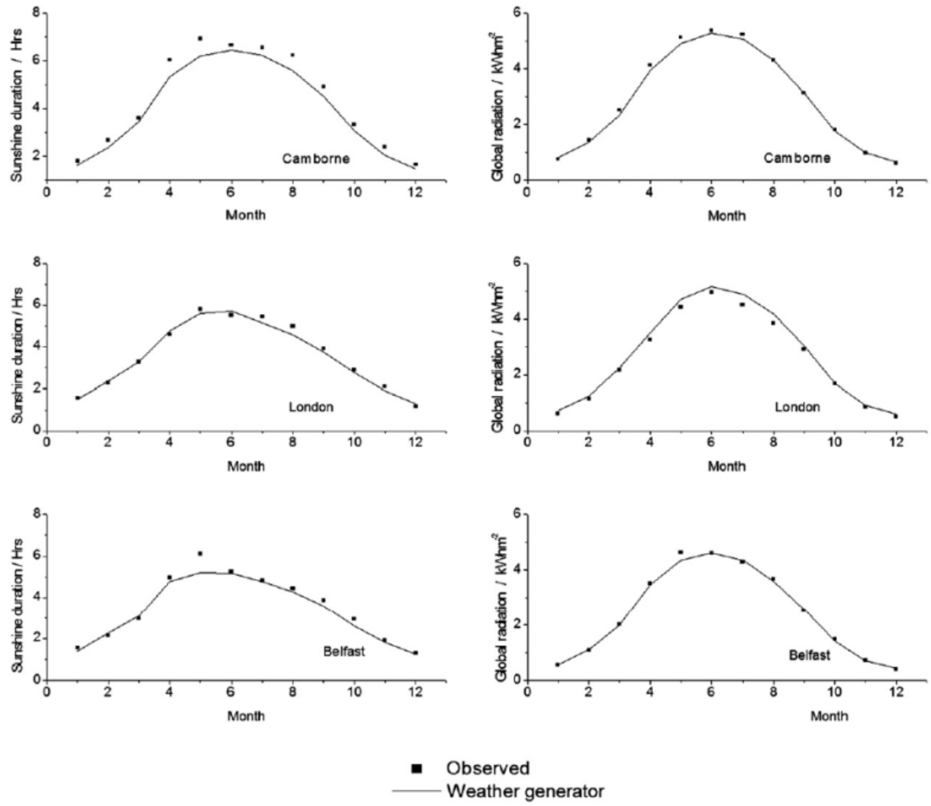

Figure 14. “Comparison between the observed and weather generator sunshine duration and global radiation for Camborne, London, and Belfast.”
Source: Eames, M, Tristan Kershaw, and David Coley. "A comparison of future weather created from morphed observed weather and created by a weather generator." *Building and Environment* 56 (2012): Figure 4, 256.

5.5.2 Transforming of historical observation

Eames, Kershaw, and Coley proposed a second method of creating future weather files, which uses the “morphing” developed by Belcher, Hacker, and Powell to transform observed weather data through a complicated process using the weather generator dataset as the baseline. This second method involved transforming the observed weather series using 10,000 sets of change factors associated with predicted change in the UKCP09 dataset in order to produce future weather files. According to Eames, Kershaw, and Coley,

> In this case, the 10,000 monthly change factors are ordered by change in monthly temperature. To produce a 50th percentile year, the 50th percentile mean change in

temperature for January is combined with the 50th percentile mean change in temperature for February and so on. [93]

The purpose of this rigorous process is to find an average year for each of the samples from the weather generator. The datasets are then combined with a representation of an average weather year or Test Reference Year (TRY), in this case, from the hourly observations (1961-1990), to produce future weather files.

Three locations were selected to compare the two methods of creating future weather files, the weather generator and the transforming method (see Table 9-Table 11). The comparison focused on the mean daily minimum temperature, mean daily maximum temperature, mean temperature, mean horizontal global irradiation, and mean diffuse irradiation for the base climate period (1961-1990) and three future periods under the A1FI high emissions scenarios. The results of the two weather file methods were similar. Both showed an increase in temperature, little change in the diffuse irradiation, and an increase in the direct solar irradiation. While the mean temperatures were similar in both weather files for all locations, the maximum and minimum temperatures were not.[94] This could be due to the difference in the dataset used for each method. It might also reflect the lack of stretch in the minimum and maximum temperatures within the morphing procedures.

The use of future weather files generated by either method, then, can be recommended for BES software. According to this research, across the century for the three sample locations, both methods showed similar mean temperatures and the same underlying climate change signals and temperature increases. Either method offers the potential for more accurate future climate information for the investigation of a building's possible responses to climate change.

The transforming method might be too complicated and time-consuming for many users. However, the weather generator method is easier to use for generating future

[93] Ibid., 259.
[94] Ibid., 261.

weather files. Eames , Kershaw, and Coley noted that the observed weather is similar to the output from the weather generator. Therefore, the use of the weather generator to predict future climate conditions can be justified.

Table 9. “Key statistics for reference weather files for Plymouth.”

		Average Daily Min Temp °C		Average Daily Max Temp °C		Mean Temp °C		Mean Global Rad Wm^{-2}		Mean Diffuse Rad Wm^{-2}	
	%	WG	M	WG	M	WG	M	WG	M	WG	M
Base		7.9	8.0	13.7	13.3	10.8	10.7	122	109	68	67
2030	10	8.5	8.7	14.3	14.0	11.3	11.4	123	109	67	67
	50	9.5	9.8	15.7	15.1	12.6	12.5	126	118	69	69
	90	10.8	11.0	17.0	16.3	13.8	13.7	128	114	68	68
2050	10	9.2	9.2	14.8	14.5	11.9	12.0	122	111	67	68
	50	10.3	10.6	16.6	16.0	13.4	13.4	130	119	68	69
	90	12.0	12.3	18.4	17.7	15.2	15.1	128	126	68	72
2080	10	10.0	10.1	15.7	15.5	12.8	12.9	128	120	67	69
	50	11.9	12.1	18.0	17.5	14.9	14.9	133	126	67	70
	90	14.1	14.6	20.9	20.0	17.4	17.4	135	126	66	71

Source: Eames, M, Tristan Kershaw, and David Coley. "A comparison of future weather created from morphed observed weather and created by a weather generator." *Building and Environment* 56 (2012): Table 2, 261.

Table 10. “Key statistics for reference weather files for Edinburgh”

		Average Daily Min Temp °C		Average Daily Max Temp °C		Mean Temp °C		Mean Global Rad Wm^{-2}		Mean Diffuse Rad Wm^{-2}	
	%	WG	M	WG	M	WG	M	WG	M	WG	M
Base		4.6	5.1	12.1	11.8	8.3	8.5	104	98	62	64
2030	10	5.2	5.7	12.7	12.4	8.9	9.2	107	97	62	63
	50	6.5	6.8	13.7	13.5	10.1	10.2	103	98	60	64
	90	7.5	8.0	15.2	14.7	11.3	11.4	107	104	61	65
2050	10	5.5	6.2	13.4	12.9	9.4	9.6	108	94	61	62
	50	7.0	7.6	14.8	14.3	10.9	11.0	105	103	61	65
	90	8.6	9.2	16.6	15.9	12.5	12.6	110	105	61	66
2080	10	6.4	7.0	14.2	13.7	10.2	10.4	110	98	61	63
	50	8.2	8.9	16.2	15.6	12.2	12.4	108	109	61	66
	90	10.8	11.3	18.5	18.0	14.6	14.7	115	106	61	65

Source: Eames, M, Tristan Kershaw, and David Coley. "A comparison of future weather created from morphed observed weather and created by a weather generator." *Building and Environment* 56 (2012): Table 3, 262.

Table 11. “Key statistics for reference weather files for London.”

	%	Average Daily Min Temp °C		Average Daily Max Temp °C		Mean Temp °C		Mean Global Rad Wm^{-2}		Mean Diffuse Rad Wm^{-2}	
		WG	M	WG	M	WG	M	WG	M	WG	M
Base		6.7	7.1	14.5	14.1	10.5	10.5	122	111	68	68
2030	10	7.2	7.8	15.1	14.8	11.1	11.3	123	111	67	68
	50	8.4	9.0	16.6	15.9	12.4	12.4	126	120	69	70
	90	9.6	10.3	18.2	17.2	13.8	13.7	128	122	68	70
2050	10	7.9	8.4	15.6	15.3	11.7	11.8	122	119	67	71
	50	8.9	9.9	17.7	16.8	13.3	13.3	130	115	68	67
	90	11.0	11.6	19.5	18.6	15.1	15.1	128	123	68	69
2080	10	8.8	9.2	16.2	16.2	12.6	12.6	128	112	67	67
	50	10.6	11.4	18.9	18.3	14.8	14.8	133	126	67	70
	90	13.4	14.0	22.0	21.0	17.4	17.4	135	128	66	68

Source: Eames, M, Tristan Kershaw, and David Coley. "A comparison of future weather created from morphed observed weather and created by a weather generator." *Building and Environment* 56 (2012): Table 4, 262.

PART 2:

RESEARCH DOCUMENTATION

Chapter 6: Research Objective

6.1 Research Methodology

Research thus far has established that future climate condition predictions are the starting point for evaluating the impacts of climate change on building envelope performance. Today, most building-related studies and assessments use current climate data with BES tools to try and predict a building's future energy performance. By using current instead of simulated future weather files, however, this method of building assessment does not reflect the changing climate and thus the predictions cannot be as accurate.[95] The use of present-day weather files to create predicted or simulated future weather files is an area of development that is more recently gaining attention. This dissertation research uses such simulated future weather files to help determine the performance of the chosen site's building envelope.

Part 2 of this dissertation is divided into three sections:

1. A definition of future climate conditions.
   The four future climate scenarios laid out in the 2007 IPCC AR4 - A1, A2, B1, and B2 - are projections of future emissions used to generate climate models. Section 5.2 details each of these scenarios. Due to time limitations, this project only focuses on the A2 scenario. This scenario represents the second highest emissions prediction.

2. A definition of the object under investigation.
   The new Hawai'i National Energy Institution (HNEI) university classroom building, a cooperative project between Project Frog (an innovative Institution

[95] Jentsch, Mark F, AbuBakr S Bahaj, and Patrick AB James. "Climate change future proofing for buildings - Generation and assessment of building simulation weather files." *Energy and Buildings* 40, no. 12 (2008), 2148.

architecture firm), the HNEI, and the UHM, was chosen as the object under investigation. The investigation focuses on reducing the annual energy consumption and heat gain of the building.

3. A focus on observation and quantification.

   The research focuses on the assessment of building envelope performance and annual energy use under the A2 climate condition scenario, and uses the metrics energy use intensity (EUI), peak cooling load, and energy consumption by end use, as forms of measurement for the final comparison of the results. The research quantifies the proposed building envelope design for each climate condition (present-day, 2050, and 2080) using three different models as the baselines from which to assess the performance of the building. These models are:

   A. Current Design model, the exact Frog building specifications of the HNEI university classroom building;
   B. ASHRAE Standard 90.1-2010 Design model, the Frog building specifications with changes according to the ASHRAE Standard;
   C. Proposed Design model, the Frog building specifications with changes based on the sensitivity study results (see chapter 9).

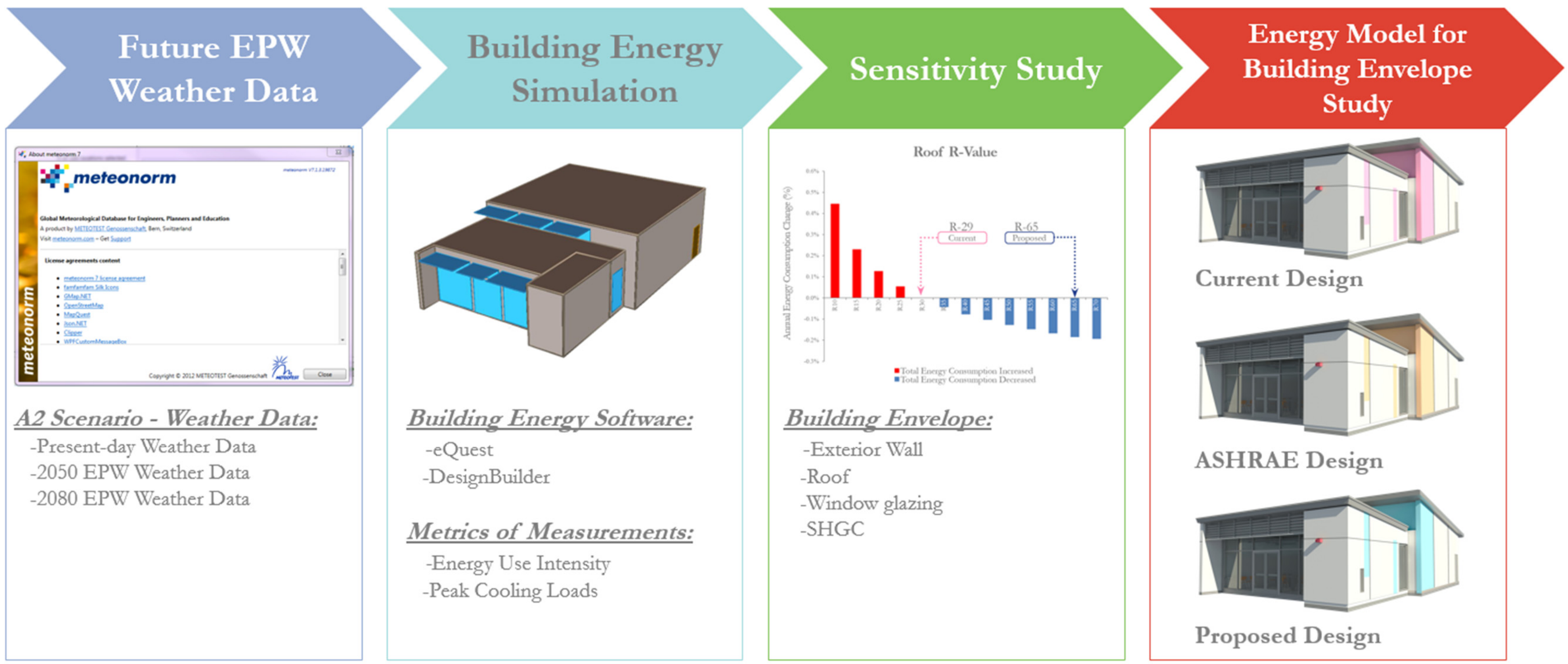

Figure 15. Research work flow diagram
Source: Author

6.2 “Morphed” EPW Weather Data

6.2.1 Location of the Weather Data Station

The weather data used for this dissertation is the Honolulu International Airport 911820 TMY3 generated by Meteonorm. The A2 (second highest emissions) projected climate scenario for the present-day, 2050, and 2080 periods was used to assess each of the building’s three design models’ potential performance. The CCWorldWeatherGen software, more accessible because it is free, provided an alternative option for producing future weather files.

6.2.2 Meteonorm

Meteonorm uses the average anomalies of 18 global models over 30 years of average climate data which are available through the 2007 IPCC AR4. Meteonorm is able to generate three scenarios for future projection: A2 (second highest emissions), A1B (balanced emissions), and B1 (low emissions). The output file format for Meteonorm is in EPW and is ready to be used in any BES software.

6.2.3 CCWorldWeatherGen

The CCWorldWeatherGen tool uses present-day observed EPW/TMY3 weather files provided by the US DOE and HadCM3 to generate future weather files based on the 2007 IPCC SRES A2 scenarios. The software is free and can be used to generate future weather files from any location provided there is a weather station in the desired location. The output file format for CCWorldWeatherGen is in EPW and is ready to be used in any BES software.

6.3 Building Energy Simulation (BES) Programs

6.3.1 DesignBuilder

DesignBuilder is a BES program, the front end of EnergyPlus, which is a high-end energy simulation engine developed by the US DOE for building performance assessment. DesignBuilder provides a range of environmental performance data such as annual energy consumption, internal comfort, and HVAC component sizes. Output is based on detailed sub-hourly simulation time steps using an EnergyPlus simulation engine and EPW weather file. Combines rapid building modeling and ease of use with state of the art dynamic energy simulation. DesignBuilder features an easy-to-use OpenGL solid modeler, which allows building models to be assembled by positioning, stretching and cutting 'blocks' in 3D space. In addition, parametric analysis screens allow you to investigate the effect of variations in design parameters on a range of performance criteria.

6.3.2 eQuest

eQuest allows users with limited simulation experience to develop 3D simulation models of a building design. These simulations incorporate building location, orientation, wall/roof construction, window properties, as well as HVAC system, day-lighting, and various control strategies. In addition, eQuest has the ability to evaluate design options for any single or combination of energy conservation measures. According to the Energy Design Resources website:

> eQuest is a sophisticated, yet easy to use, freeware building energy use analysis tool that provides professional-level results with an affordable level of effort. eQuest was designed to allow you to perform detailed comparative analysis of building designs and technologies by applying sophisticated building energy and design development building creation wizards.[96]

[96] 2014. Energy Design Resources. May 28. https://energydesignresources.com/resources/software-

eQUEST features a building creation wizard that walks through the process of creating an effective building energy model. This involves following a series of steps that describe the features of the design that would impact energy use, such as architectural design, HVAC equipment, building type and size, floor plan layout, construction materials, area usage and occupancy, and lighting system. After compiling a building description, eQUEST produces a detailed simulation of the building, as well as an estimate of how much energy it would use. Although these results are generated quickly, this software utilizes the full capabilities of DOE-2.2.

Within eQUEST, DOE2.2 performs an hourly simulation of the building design for a one year period. It calculates heating or cooling loads for each hour of the year, based on the 16 factors such as walls, windows, glass, people, plug loads, ventilation, and more. DOE-2.2 also simulates the performance of fans, pumps, chillers, boilers, and other energy consuming devices. During the simulation, DOE-2.2 also tabulates the building's projected use for various end uses.

6.4 Sensitivity Study

In the sensitivity study, four potential mitigation measures concerning the building envelope design were considered. These variables were chosen based on their relatively high influence coefficients (a measure of how sensitive the building energy use is to changes in the design variables). These four variables are the exterior wall R-value, the roof R-value, the window glazing U-value, and the SHGC. Different values were considered for each design variable to determine the most energy-efficient measures.

The Current Design model was chosen as the subject for analysis of the different values of each design variable. The present-day EPW weather data along with the BES program,

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tools/equest.aspx?utm_source=twitter&utm_medium=tweet&utm_campaign=2011-marketing. (accessed January 29, 2016)

DesignBuilder, were used to analyze the performance of the building envelope design. The results for this study contributed to the development of the Proposed Design model, a model intended to be more adaptive to climate change than the Current Design and ASHRAE Design models.

6.5 Energy Model

To understand the impact of climate change on the building's energy performance, the Frog buildings were modeled for the present study. The annual energy consumption of its HVAC system was evaluated using the BES program, eQuest. Present-day and future EPW weather data were used for the weather input in the simulations to determine the changing climate's impacts on the building's energy use. The mechanical systems of the energy models were set at a constant variable (SEER 13) in order to identify the changes in building envelope and how effective these are in reducing energy use. The operation schedule of the building followed the school's current hours of operation—7 am to 5 pm, Monday through Friday.

Chapter 7: Constructing Future Weather Files

Buildings are generally adaptive to changes in climate. Nevertheless, climate thresholds exist beyond which buildings cease to be safe for occupation. This occurs to buildings that lack the proper thermal fabric to protect them from exposure to unforeseen climate extremes. With the use of simulated future weather files, however, buildings can be designed, modified, and improved to meet the challenges presented by changing climate conditions in the future.[97] This project used both Meteonorm and CCWorldWeatherGen software to generate simulated future EPW weather data for scenario planning. Scenario planning looks at a range of alternative futures and projects future building conditions within each scenario to identify and apply different strategies and values to the building design.

7.1 CCWorldWeatherGen

The CCWorldWeatherGen tool uses the 2007 IPCC AR4 model summary data of the HadCM3 model, available from the IPCC Data Distribution Center (DDC). The tool, based in Microsoft® Excel, transforms present-day observed EPW/TMY3 weather files into climate change future EPW/TMY3 weather files, which are compatible with the majority of building energy simulation (BES) software.[98] The future performance of the structures we build depends on the decisions we make today.

Data:

- Future data: IPCC
    - Fourth Assessment Report, 2007

[97] Roaf, Sue, David Crichton, and Fergus Nicol. Adapting Buildings and Cities for Climate Change: A 21st. Amsterdam: Architectural Press, 2005: 58.
[98] *Sustainable Energy Research Group.* October 2013. http://www.energy.soton.ac.uk/ccworldweathergen/ (accessed March 25, 2015).

        - Scenario: A2 (second highest emissions)
    - Tool: CCWorldWeatherGen version 1.8
        - EnergyPlus/Typical Meteorological Year 3 weather files (EPW/TMY3)
        - IPCC 2007 data
        - Time series adjustment: morphing

          Adjust present-day weather file by the changes to climate forecast by global circulation models and regional climate models.[99]

7.1.1 Basis requirements for running the CCWorldWeatheGen tool

1. CCWorldWeatherGen tool has been tested on computers running Microsoft® Excel Windows XP and Windows 7 operating systems.
2. A valid installation of Microsoft® Excel on your local hard drive. CCWorldWeatherGen has been tested with the Microsoft® Excel 2003, 2007, and 2010 versions.
3. A present-day EPW/TMY3
    a. The US Department of Energy (DOE) provides weather files, in EPW format, for more than 2,100 locations throughout the world.
    b. These files can be accessed via the following web link: http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data.cfm.
4. Summary data of the HadCM3 A2 climate change model predictions can be downloaded from the IPCC DCC web link: http://www.ipcc-data.org/sres/hadcm3_download.html.

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[99] Belcher, SE, JN Hacker, and Dianne S Powell. "Constructing design weather data for future climates." *Building Services Engineering Research and Technology*, 2005: 50.

7.1.2 Preparing the CCWorldWeatherGen tool for use

1. CCWorldWeatherGen v1.8 can be downloaded via the following web link: http://www.energy.soton.ac.uk/ccworldweathergen/.
2. After downloading the file *CCWorldWeatherGen.exe* please run it for installation of the CCWorldWeatherGen tool. The file is self-extracting. It is NOT RECOMMENDED to change the default installation path *(C:\CCWorldWeatherGen)*. A program folder called CCWorldWeatherGen is added to the Windows Start Menu during installation.
3. The CCWorldWeatherGen tool can be launched right after installation. However, before being able to use it, you need to make sure that you are in possession of present-day EPW/TMY3 files and have obtained the required HadCM3 data.

A more detailed guide for generating EPW future weather data using CCWorldWeatherGen can be found at the following website:
http://www.energy.soton.ac.uk/ccworldweathergen/.

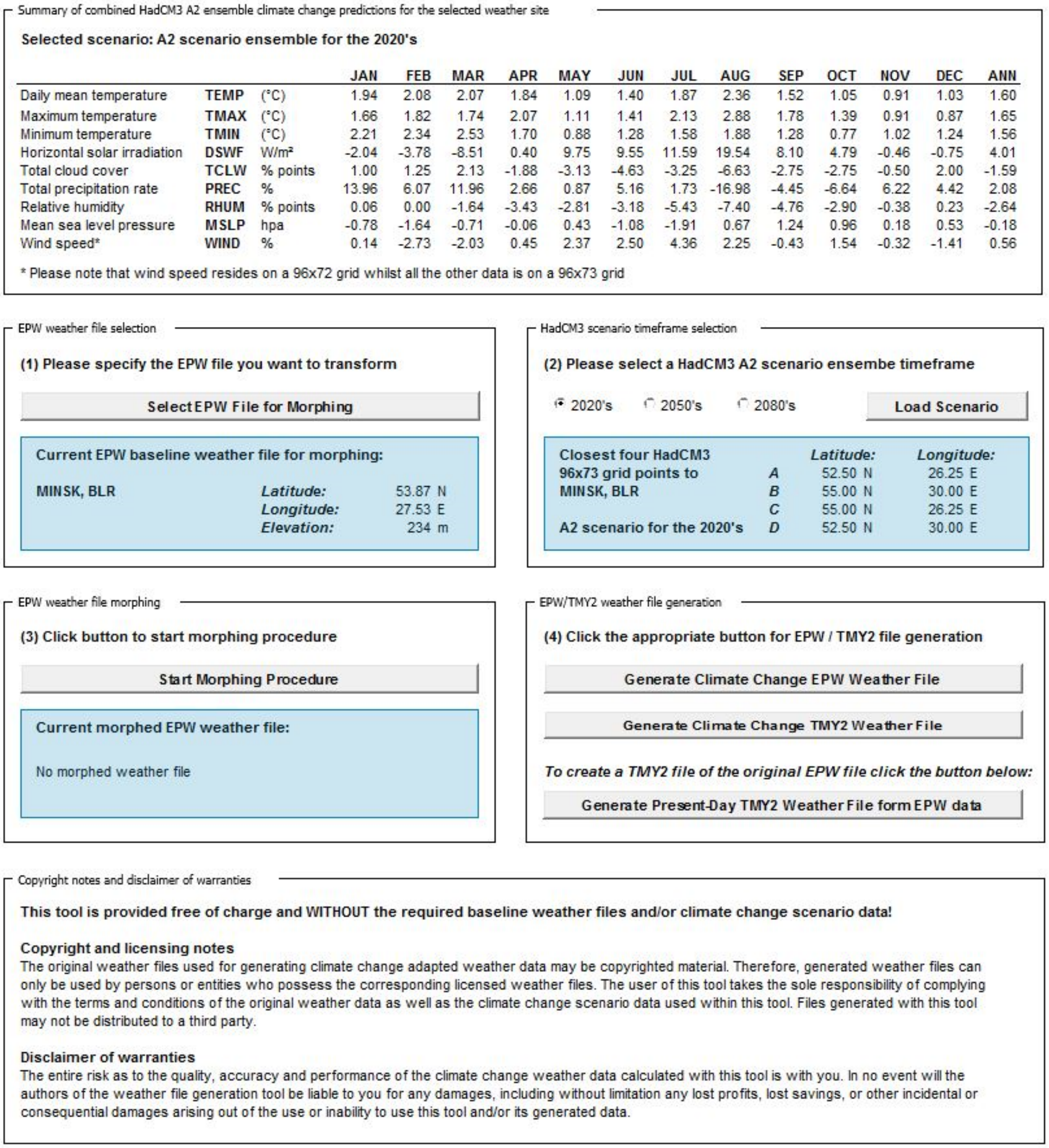

Figure 16. CCWorldWeatherGen tool
Source: Author

7.1.3 Results from the CCWorldWeatherGen

For data evaluation purposes, the future climate data discussed below compares three weather stations: Barbers Point, Hilo, and London. Barbers Point and Hilo, both located in Hawai‘i, and were chosen because of their proximity to the site location chosen for this research, the Honolulu International Airport weather station. Due to a technical error, the CCWorldWeatherGen tool could not generate future weather data for the Honolulu International Airport weather station. London was selected based on a recommendation in the CCWorldWeatherGen manual.

Table 12 to_table 14 show the average daily maximum dry-bulb temperature, average daily minimum dry-bulb temperature, average daily dry-bulb temperature, average global radiation, average direct radiation, average diffuse radiation, average humidity, and average daily wind speed for the baseline climate model and two future periods (2050 and 2080) for the three locations (Barbers Point, Hilo, and London). The emissions scenario for this investigation is the A2 storyline (second highest emissions). For the most part, all three locations have shown an increase in dry-bulb temperature and diffuse radiation, relative humidity, and wind speed. In contrast, the average global radiation and direct radiation are decreasing for the two locations in Hawai‘i, while London is experiencing an increase in solar radiation.

To conclude, as evident from the analysis above, the CCWorldWeatherGen software ‘morphing’ approach is appropriate for transforming present-day weather data into climate change weather data. This tool and approach can be implemented during the early schematic phase of the design to evaluate the performance of the building design under various changing climate conditions.

Table 12. Present-day and future EPW weather data under the A2 scenario for Barbers Point, Hawai‘i

Barbers Point	Avg Daily Max Dry-Bulb °C	Avg Daily Min Dry-Bulb °C	Avg Daily Mean Dry-Bulb °C	Avg Global Rad (wh/sq.m)	Avg Direct Rad (wh/sq.m)	Avg Diffuse Rad (wh/sq.m)	Mean Humidity (%)	Avg Mean Daily Wind Speed (m/s)
Present-Day	29.36	20.74	24.77	5284.75	4766.50	2118.33	66.73	3.60
2050	31.04 ↑	22.41 ↑	26.45 ↑	5255.67 ↓	4032.17 ↓	2513.75 ↑	67.23 ↑	3.58 ↑
2080	32.06 ↑	23.44 ↑	27.48 ↑	5211.92 ↓	3922.08 ↓	2544.75 ↑	68.06 ↑	3.60 ↑

Source: Author

Table 13. Present-day and future EPW weather data under A2 scenario for Hilo, Hawai‘i

Hilo	Avg Daily Max Dry-Bulb °C	Avg Daily Min Dry-Bulb °C	Avg Daily Mean Dry-Bulb °C	Avg Global Rad (wh/sq.m)	Avg Direct Rad (wh/sq.m)	Avg Diffuse Rad (wh/sq.m)	Mean Humidity (%)	Avg Mean Daily Wind Speed (m/s)
Present-Day	26.80	19.84	23.07	4507.50	3501.33	2031.08	79.65	3.26
2050	28.49 ↑	21.53 ↑	24.76 ↑	4491.75 ↓	2724.33 ↓	2148.83 ↑	80.31 ↑	3.24 ↑
2080	29.62 ↑	22.68 ↑	25.90 ↑	4459.83 ↓	2655.08 ↓	2259.83 ↑	80.97 ↑	3.27 ↑

Source: Author

Table 14. Present-day and future EPW weather data under A2 scenario for Gatwick, London

London	Avg Daily Max Dry-Bulb °C	Avg Daily Min Dry-Bulb °C	Avg Daily Mean Dry-Bulb °C	Avg Global Rad (wh/sq.m)	Avg Direct Rad (wh/sq.m)	Avg Diffuse Rad (wh/sq.m)	Mean Humidity (%)	Avg Mean Daily Wind Speed (m/s)
Present-Day	14.00	6.06	10.20	2756.50	2030.42	1618.75	79.31	3.24
2050	16.05 ↑	7.77 ↑	12.09 ↑	2917.75 ↑	2289.3 ↑	1588.83 ↑	75.90 ↑	3.26 ↑
2080	17.70 ↑	9.27 ↑	13.66 ↑	2973.83 ↑	2414.67 ↑	1560.75 ↑	74.24 ↑	3.28 ↑

Source: Author

7.2 Meteonorm

Meteonorm, like CCWorldWeatherGen, uses the 2007 IPCC AR4 model summary data of the HadCM3 model to generate EPW future weather file for BES programs. The software uses the same algorithm and theory to generate EPW future weather data. The software itself is much more powerful than CCWorldWeatherGen because of its capability to generate three out of the four scenarios described in the SRES report. To investigate the certainties of Meteonorm, the Honolulu International Airport weather station was selected as the primary EPW weather data for the A2 scenario as predicted by the IPCC. The A2 scenario represents the second highest emissions scenario.

Data:

- Future data: IPCC
  - Fourth Assessment report (AR4), 2007
  - Scenario: A2 (second highest emissions)
- Tool: Meteonorm version 7.0
  - Climate normal 1991 – 2010
  - IPCC 2007 data
  - Stochastic generator:

    > Synthetic weather time series are generated using empirically-derived statistics. While this method is computationally cheap, it does require large data sets to refine the model to give appropriate statistics and fix unknown model coefficients, and the weather series it produces may not always be meteorologically consistent, as noted by Belcher, Hacker, and Powell.[100]

Process:

To obtain a weather file, five steps must be followed:

1. Locations: Select the locations for which you want to run Meteonorm.
2. Modifications: Modify the location-specific settings. For this project, the default settings were retained.

[100] Belcher, SE, JN Hacker, and Dianne S Powell. "Constructing design weather data for future climates." *Building Services Engineering Research and Technology*, 2005: 50.

3. Data: Adjust data settings.
4. Format: Set the output format.
5. Output: Calculate and store the results.

A more detailed guide for generating EPW future weather data using Meteonorm can be found via the following web link: http://www.meteonorm.com/en/downloads/documents.

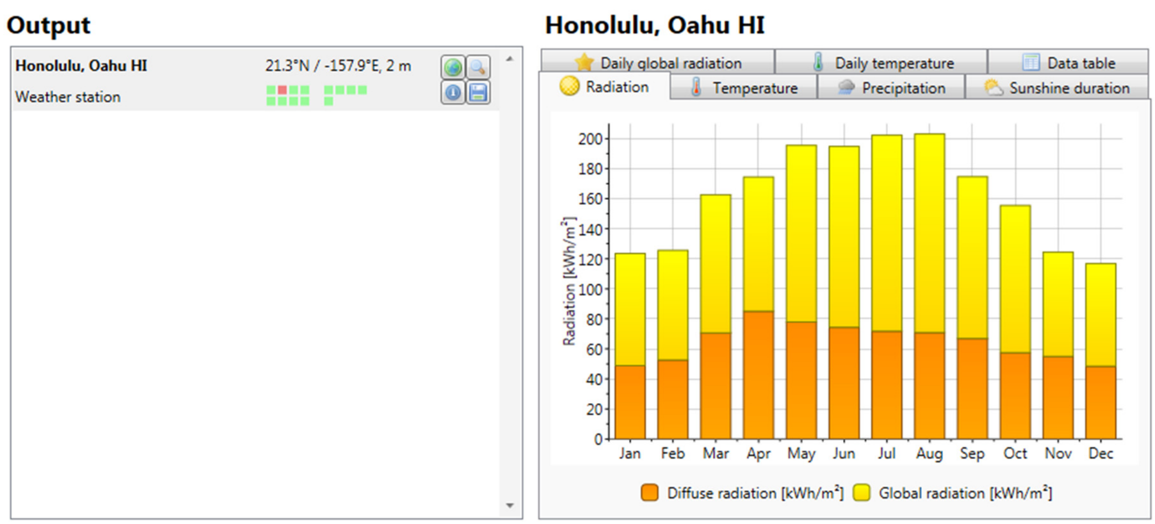

Figure 17. Meteonorm EPW weather data output for Honolulu International airport weather station
Source: Author

7.2.1 Results from Meteonorm

The Honolulu International weather station EPW weather file, downloaded using Meteonorm software, is the subject for investigation for this study. Figure 18 shows the monthly mean temperature of the original EPW weather file compared to climate change adapted versions of this weather data for 2050 and 2080. A clear increase in average dry-bulb temperatures is visible from one time step to the next. This results in a predicted temperature rise of about 1-2 °C from current levels to the end of the twenty-first century.

Table 15. Present-day and future EPW weather data under the A2 scenario for Honolulu, Hawai'i

Honolulu Int. AP	Avg Daily Max Dry-Bulb °C	Avg Daily Min Dry-Bulb °C	Avg Daily Mean Dry-Bulb °C	Avg Global Rad (wh/sq.m)	Avg Direct Rad (wh/sq.m)	Avg Diffuse Rad (wh/sq.m)	Mean Humidity (%)	Avg Mean Daily Wind Speed (m/s)
Present-Day	29.97	19.38	24.56	5345.58	5076.17	2001.08	67.58	3.92
2050	31.19	21.53	26.32	5290.33	4679.08	2205.50	66.58	4.42
2080	32.40	22.57	27.36	5281.50	4727.83	2155.33	66.75	4.50

Source: Author

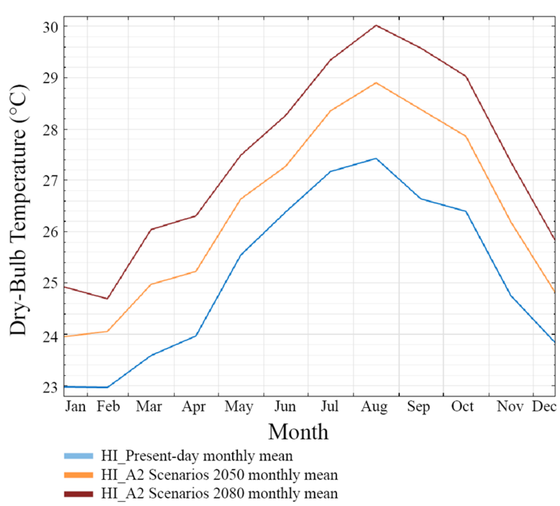

Figure 18. Honolulu, monthly mean temperature, present-day and future EPW weather data future EPW weather data under A2 scenario (second highest emissions)
Source: Author

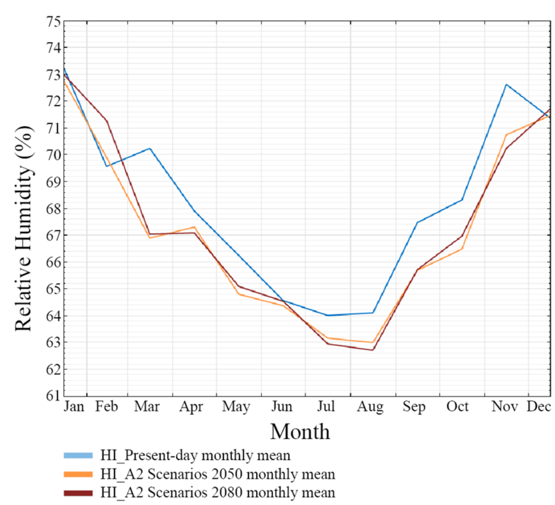

Figure 19. Honolulu, monthly mean temperature, present-day and future EPW weather data under A2 scenario (second highest emissions)
Source: Author

This increase can be considered very significant for living conditions in urban areas like Honolulu, which also experience urban heat island effects that further increase the implications of climate change. As a result of the rising temperatures, the relative humidity is expected to drop by the 2080s by a total of about 5 percentage points from today's values (see figure 19). Interestingly, the temperature increase shown in the analyzed data is not linked to a corresponding increase in solar radiation. As can be seen in figure 20 the monthly mean daily global horizontal radiation is predicted to decrease marginally only over time, with the only significant change being a 2.1% decrease from today's value by September of 2080. It is interesting to note that the two hot months of April and May show no significant change. Furthermore, some months, like June and July, even show a gradual solar radiation decrease of up to 1%.

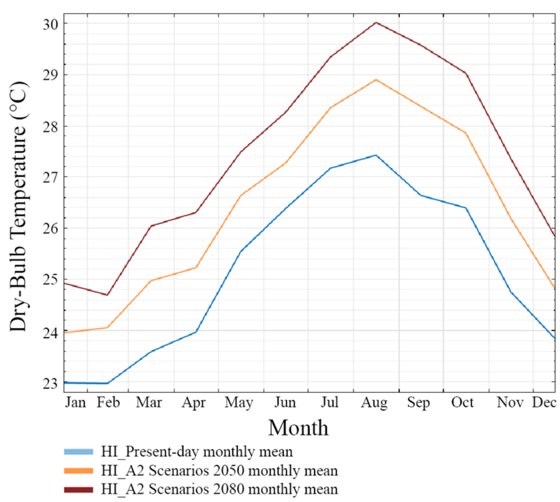

Figure 20. Honolulu, monthly mean global horizontal radiation, 'present-day' and future EPW weather data under A2 Scenario (second highest emissions)
Source: Author

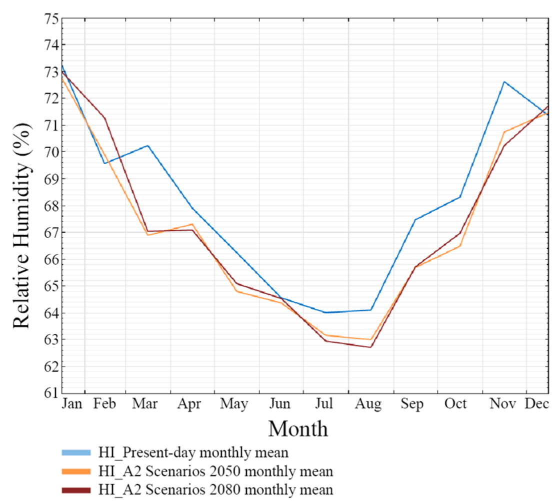

Figure 21. Honolulu, monthly mean direct normal radiation, 'present-day' and future EPW weather data under A2 Scenario (second highest emissions)
Source: Author

The analysis of the weather data shows changes in the weather patterns of 2050 and 2080 that reflect expected predicted climate change. A phenomenon, recognized by many climate scientists, called global dimming and brightening, is recorded here in the predictions. Global dimming and brightening is believed to be caused by the substantial emissions of aerosol in the atmosphere that then causes an atmospheric brown cloud to form and block out a majority of the solar radiation (see section 7.3 for more details).

From the results of both the Meteonorm and CCWorldWeatherGen tool studies above, it can be concluded that for tropical climates, the ‘morphing’ approach is well suited for transforming present-day weather data into climate change weather data. Climate change adapted versions of the present-day weather files currently used within the building industry should be used for all building design projects in order to more accurately evaluate the building’s potential future performance and for appropriately sizing the HVAC systems.

7.3 Global Dimming & Brightening

Observations from the worldwide network of pyranometers, the measurement devices that record surface solar radiation (SSR), indicate that the solar radiation incidence at the Earth’s surface underwent substantial decadal variations in the second half of the twentieth century in the Northern Hemisphere, according to Martin Wild and Edgar Schmucki in their journal article, “Assessment of global dimming and brightening in IPCC-AR4/CMIP3 models and ERA40.” From 1950 to 1980, a reduction of SSR, referred to as global dimming, was measured, and from 1980 to 2000, a partial recovery of SSR, called global brightening, was measured. Both Wild and Schmucki and the 2013 IPCC report agree that the causes of global dimming and brightening are related to the substantial aerosol levels in the atmosphere.[101]

Aerosols influence climate via clouds that scatter light and change the Earth’s reflectivity, both directly and indirectly.[102] Aerosols influence climate directly by decreasing the SSR through the scattering and absorption of solar radiation, and

[101] Wild, Martin, and Edgar Schmucki. "Assessment of global dimming and brightening in IPCC-AR4/CMIP3 models and ERA40." *Climate Dynamics* 37 (2010), 1671.
[102] Wild, Martin. "Enlightening Global Dimming and Brightening." *Bulletin of the American Meteorological Society* 93 (2012), 30.

indirectly by increasing cloud reflectivity through the emission of sulfur (SO_2) into the atmosphere (see figure 22).[103] The SO_2 in the atmosphere serves as a cloud condensation nuclei, which leads to increasing cloud reflectivity. On a global scale, these indirect aerosol effects typically work in opposition to GHGs and cause cooling. While GHGs disperse widely and have a consistent impact from region to region (see Table 15), aerosol effects are less consistent due to the particles' relationship with clouds.[104] In essence, the reduction of SSR from 1950 to 1980 can be explained by the increases in aerosol levels.

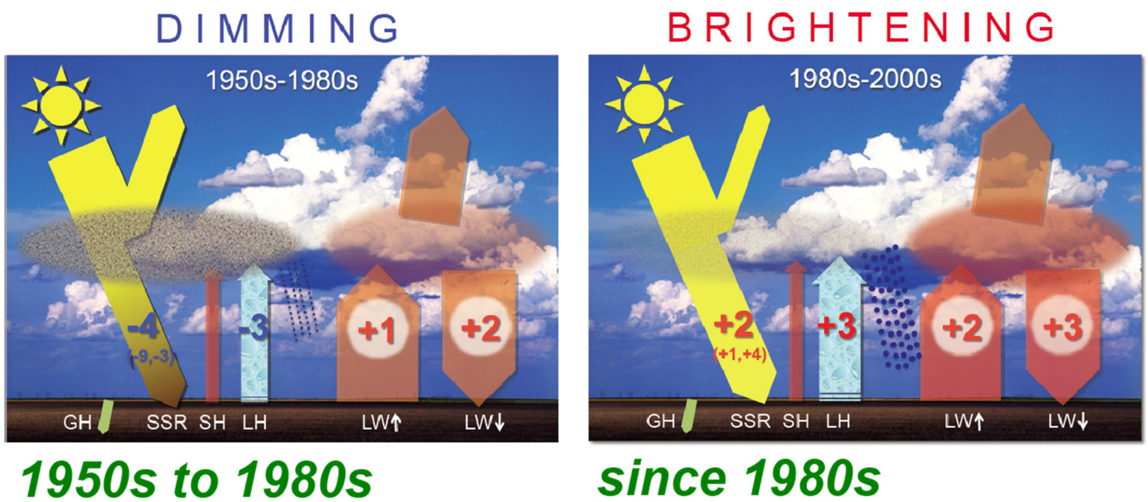

Figure 22. Schematic representation of "dimming" and "brightening" periods over land surface.
Source: Wild, Martin. "Enlightening Global Dimming and Brightening." *Bulletin of the American Meteorological Society* 93, (2012): Figure 1, 28.

Figure 22 illustrates the trends in global dimming and brightening during the second half of the last century. The dimming period on the left shows the decline of SSR (-4) and how it outweighed the increase of thermal radiation (+1) (LW↓) thus counteracting global warming, causing only a small increase in surface thermal emission (+2) (LW↑). The brightening period on the right shows an increase of thermal radiation (+2) (LW↓) and surface thermal emission (+3) (LW↑). Wild, in his article, "Enlightening

103 Ibid.
104 NASA: Earth Observatory. "Aerosols and Clouds (Indirect Effects)." n.d.. http://earthobservatory.nasa.gov/Features/Aerosols/page4.php (accessed April 30, 2015)

Global Dimming and Brightening," noted that at this point, the effects of GHGs are no longer masked by the dimming effects of aerosols. The rapid increase in warming and a stronger evaporation rate indicate that the global warming trend is back to normal after 1980.[105]

Other studies show both an increase of SO_2 and Black Carbon (BC) emissions during the global dimming period (1950-1980) and a decrease after 1980 due to a substantial reduction of aerosol emissions from the United States, Europe, and Asia at that time (see figure 23). BC is the strongest light-absorbing component of particulate matter (PM) as well as the most effective form of PM by mass at absorbing solar energy per unit of mass in the atmosphere. According to Erika Sasser, James Hemby, and their co-authors in the 2012 EPA "Report to Congress on Black Carbon," BC can absorb a million times more energy than CO_2.[106] Wild discusses the likely connection of global dimming to SO_2 and BC emissions. He writes the following about the worldwide decrease in aerosol emissions:

> This decrease is attributed to the implementation of air quality measures in industrialized countries as well as to major economic crises (e.g., the breakdown of the Communist system in Eastern Europe and Russia in the late 1980s and the Asian financial crisis in the 1990s). These emission histories fit with the observed dimming/brightening tendencies and suggest that anthropogenic air pollution may play a significant role in the explanation of SSR variations.
>
> Distinct aerosol trends that match with dimming/brightening are also observed in remote locations far away from pollution sources, such as in Greenland, the Canadian Artic, or over oceans, pointing to the large-scale distribution of these pollutants over the entire Northern Hemisphere. In the Southern Hemisphere, however, there is less evidence for significant anthropogenic pollution and no sign of trend reversal.[107]

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105 Wild, Martin. "Enlightening Global Dimming and Brightening." *Bulletin of the American Meteorological Society* 93 (2012), 28.

106 Sasser, Erika, James Hemby, et al. *Report to Congress on Black Carbon: Department of the Interior, Environment, and Related Agencies Appropriations Act, 2010.* United States Environmental Protection Agency, 2012.

107 Wild, Martin. "Enlightening Global Dimming and Brightening." *Bulletin of the American Meteorological Society* 93 (2012), 30.

Figure 23 shows the annual SO_2 emissions estimated from 1950 to 2000 over the Northern Hemisphere, Southern Hemisphere, and the entire globe. The increase of SO_2 emissions from 1950 to 1980 parallels the dimming period in the Northern Hemisphere. Surprisingly, the Southern Hemisphere was unaffected. By 1980, the trend reversed as SO_2 emissions decreased globally (see figure 22). Wild noted that the majority of aerosol emissions are distributed by continents such as North America, Europe, and Asia that are mostly in the Northern Hemisphere, which possibly explains the decline in SO_2 emissions after 1980 (see figure 22) in only the Northern Hemisphere; this would also explain why the Southern Hemisphere was unaffected.

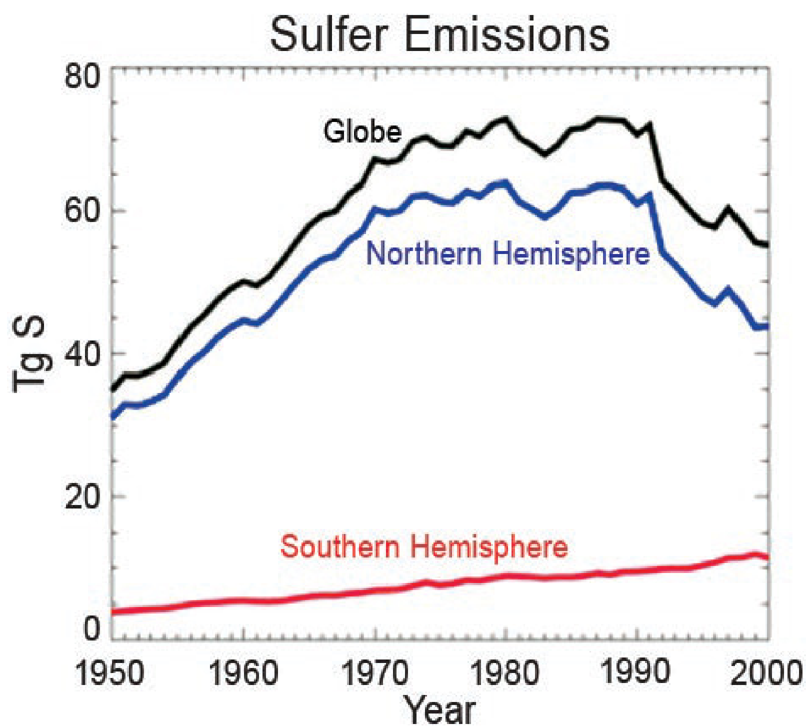


Figure 23. Annual sulfur emission estimates from 1950 to 2000 over the Northern Hemisphere, the Southern Hemisphere, and the entire globe.
Source: Wild, Martin. "Enlightening Global Dimming and Brightening." *Bulletin of the American Meteorological Society* 93 (2012): Figure 3, 30.

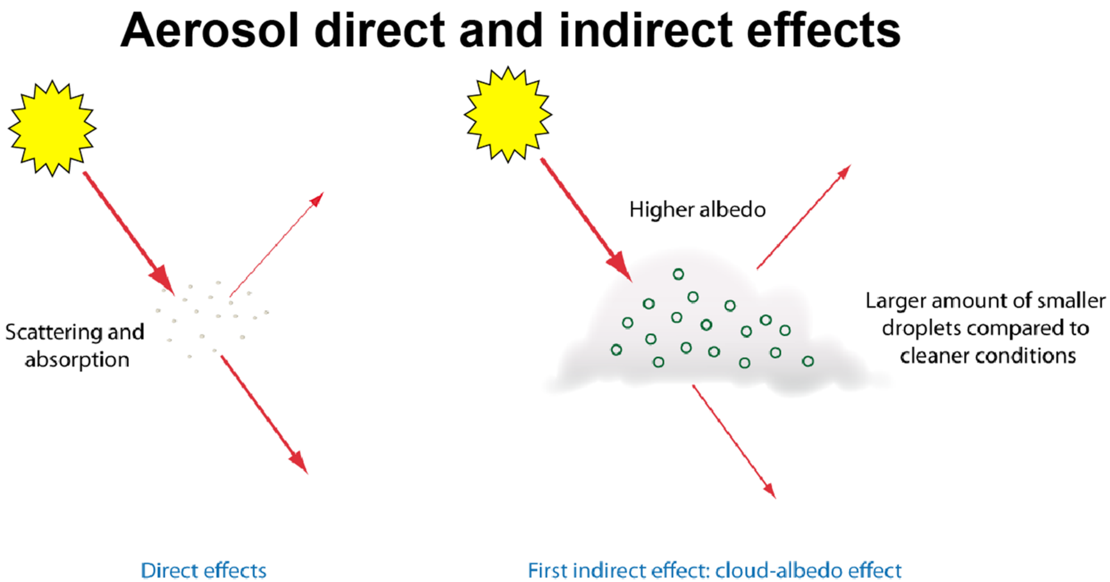


Figure 24. Illustration of both direct and indirect aerosol effects in reducing the amount of solar radiation reaching the earth's surface
Source: Wild, Martin. *Dimming and Brightening: Aerosols and Global Warming*. Presentation, NCRR Climate, Swiss Climate Research Conference, Bern, Switzerland. Oct 12, 2012.

Table 16 below presents the locations experiencing this global dimming and brightening phenomenon. The left column represents the overall decline of SSR measured at the sites in the US, Europe, China, Japan, and India during the global dimming period (1950-1980). The middle column shows a period of brightening (1980-2000) with increased SSR to all sites except India.[108] India continues to allow large aerosol emissions, which could explain why global dimming still affects India, while the other countries listed have decreased their emissions either due to air quality laws or economic crisis, as noted by Wild.[109] It may be concluded that the decline of aerosol emissions for most of these countries is causing global brightening to increase. See appendix A.

[108] Ibid., 28.
[109] Ibid., 30.

Table 16. “Observed tendencies in surface solar radiation”

	1950 - 1980	1980 – 2000	After 2000
USA	-6	5	8
Europe	-3	2	3
China/Mongolia	-7	3	-4
Japan	-5	8	0
India	-3	-8	-10

Source: Wild, Martin. "Enlightening Global Dimming and Brightening." Bulletin of the American Meteorological Society, 2012: Figure 2, 29.

The aerosol type plays an important role in determining how it will affect clouds. Where reflective aerosols tend to brighten clouds and make them last longer, the BC from soot can have the opposite effect. According to Veerabhadran Ramanathan and Gregory Carmichael in their article, "Global and regional climate change due to black carbon,” the anthropogenic sources of BC are mostly concentrated in the tropics climate zone where solar irradiance is the highest. BC, as noted earlier, is the main absorber of visible solar radiation in the atmosphere and is globally distributed through the burning of biomass and through the activities of the domestic/residential sector. Given its high absorbing quality, BC is able to mix with other aerosols as it travels across the globe; together, these form transcontinental plumes of atmospheric brown clouds.[110] Brown clouds are capable of blocking solar radiation and causing global dimming on the surface. Thus, global dimming could have been caused by the mixture of BC and aerosols, or brown clouds, in the atmosphere. For the most part, SSR shows a strong relationship between global dimming and brightening, which also parallels air pollution patterns.

110 Ramanathan, Veerabhadran, and Gregory Carmichael. "Global and regional climate change due to black carbon." *Nature geoscience* 1 (2008), 221.

Chapter 8: Design Project Introduction

8.1 Building Description

The building chosen for the research phase of this dissertation is one of two identical Frog college classroom buildings currently under construction. The project is a collaboration between Project Frog, the HNEI, and the UHM. The design intent for each of these buildings is to create state-of-the-art classrooms for quality learning and a well-equipped facility to monitor building performance. The HNEI was funded by the Office of Naval Research in 2009 to purchase and construct five modular Frog buildings. The design is pre-engineered and incorporates passive design elements that decrease energy demand. Three Frog buildings have already been built, one on O'ahu and two on Kauai. HNEI was in discussion with other sites around the state and finally selected the UHM campus for the two remaining Frog buildings. As of right now (February 2016), the UHM Frog buildings are under construction.

Figure 25. Frog building during construction phase
Source: Author

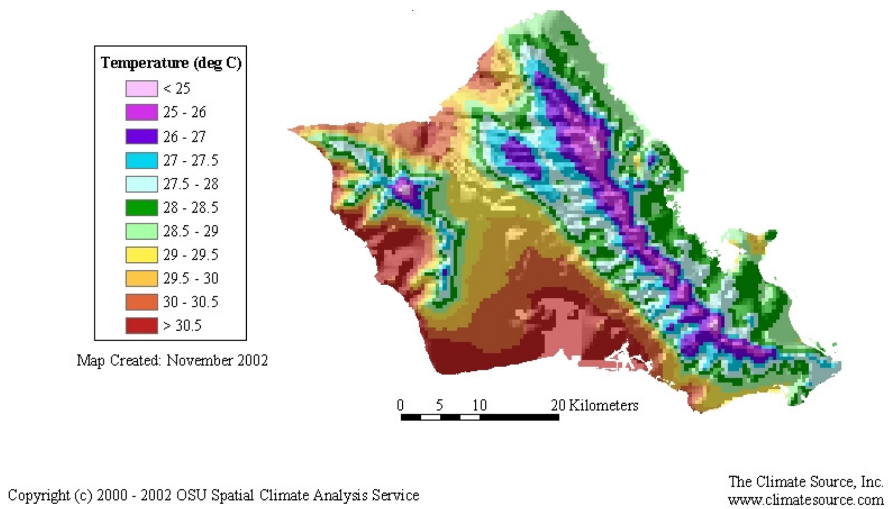
The two 1,440 square-foot Frog buildings, identical to each other, are designed by Project Frog, a San Francisco-based design and manufacturing firm. According to Project

Frog, the design provides air quality and thermal comfort management through the use of natural convection and a mixed-mode air conditioning system to reduce the dependence year-round on mechanized systems. Optimized daylighting and glare reduction provides high quality illumination for over 95 percent of daylight hours, keeping the electrical lights off during most of the school year. The design reduces energy consumption, construction waste, and operating expenses, while providing spaces that are adaptable for a variety of uses. The goal of HNEI is to analyze the performance of these energy systems for potential future Navy applications in the Pacific region. The research intent is to evaluate the energy consumption, visual quality (lighting, daylighting, and glare), and comfort performance of the structures in different microclimates in Hawaiʻi.

The focus of this dissertation research parallels the goals of HNEI. This research also focuses on analyzing the performance of energy systems for potential future improvements by using simulated future EPW weather data with BES software to assess the energy consumption, heat gain through building envelope, and peak cooling load of the building under the A2 scenario.

8.2 Climate Condition

Honolulu is classified as climate zone 1A, hot and humid, by the ASHRAE Standard 90.1 – 2013 (see figure 27). The closest national weather station to the research site is located at the Honolulu International Airport (HNL), five miles from the UHM campus (see figure 26). Meteonorm was used as the primary software for generating present-day observed EPW weather data and simulated future EPW weather data for two future time periods, 2050 and 2080. The simulated future EPW weather data will be simulated under the A2 scenario.



Honolulu International Airport UHM Campus

Figure 26. ”PRISM 1961-1990 July Mean Maximum Temperature Oahu, Hawaii” Source: The Climate Source, Inc. “Mean Monthly and Annual Maximum, Minimum, and Mean Temperature Hawaii.” 2003. http://www.climatesource.com/hi/fact_sheets/fact_tmax_hi.html (accessed April 21, 2015).

Hawai‘i is generally known for its tropical climate and relatively high temperature, humidity, and precipitation levels. These conditions vary, however, relative to the diverse topographical conditions throughout the islands. For example, UHM is located in Mānoa Valley, southwest of the Ko‘olau Mountain Range, where it receives above average amounts of precipitation. This results in higher humidity levels and lower temperatures when compared to many other areas surrounding Honolulu. The mean maximum temperatures on the windward side (northeast) of Honolulu are lower than those at Barbers Point (west) of Honolulu (see figure 26).

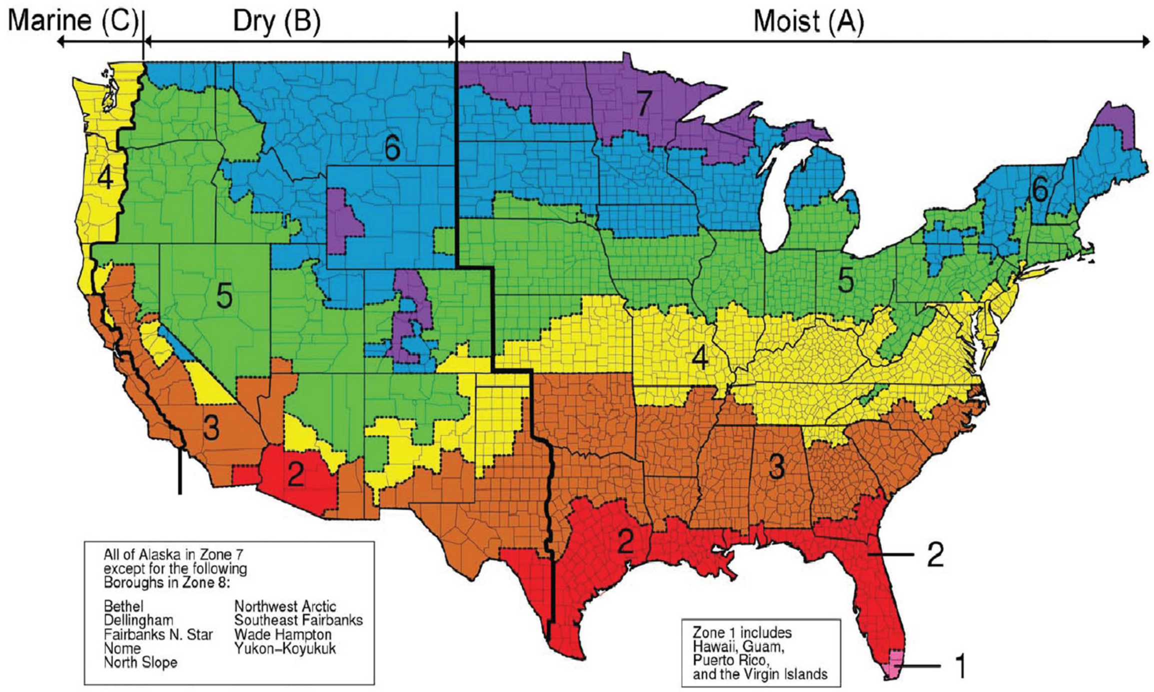


Figure 27. Climate zone map
Source: ASHRAE, "Standard 90.1-2013: Energy Standard for Buildings Except Low-Rise Residential Buildings. 2013." https://www.ashrae.org/resources--publications/bookstore/standard-90-1 (accessed April 3, 2015): 164.

8.3 Building Information

Site Location:

Address: 1776 University Avenue, Honolulu, HI 96822
Tax Map Key: 2-8-15:01

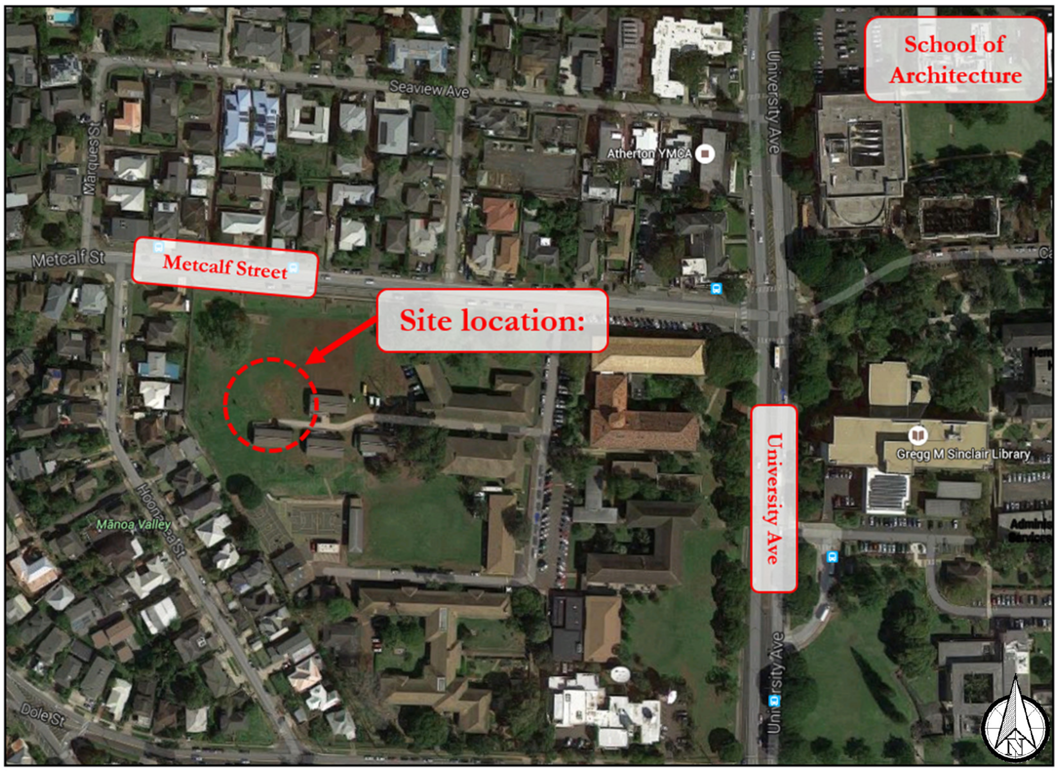


Figure 28. Site location for the Frog buildings
Source: Author

Figure 29. Site photo A
Source: Author

Figure 30. Site photo B
Source: Author

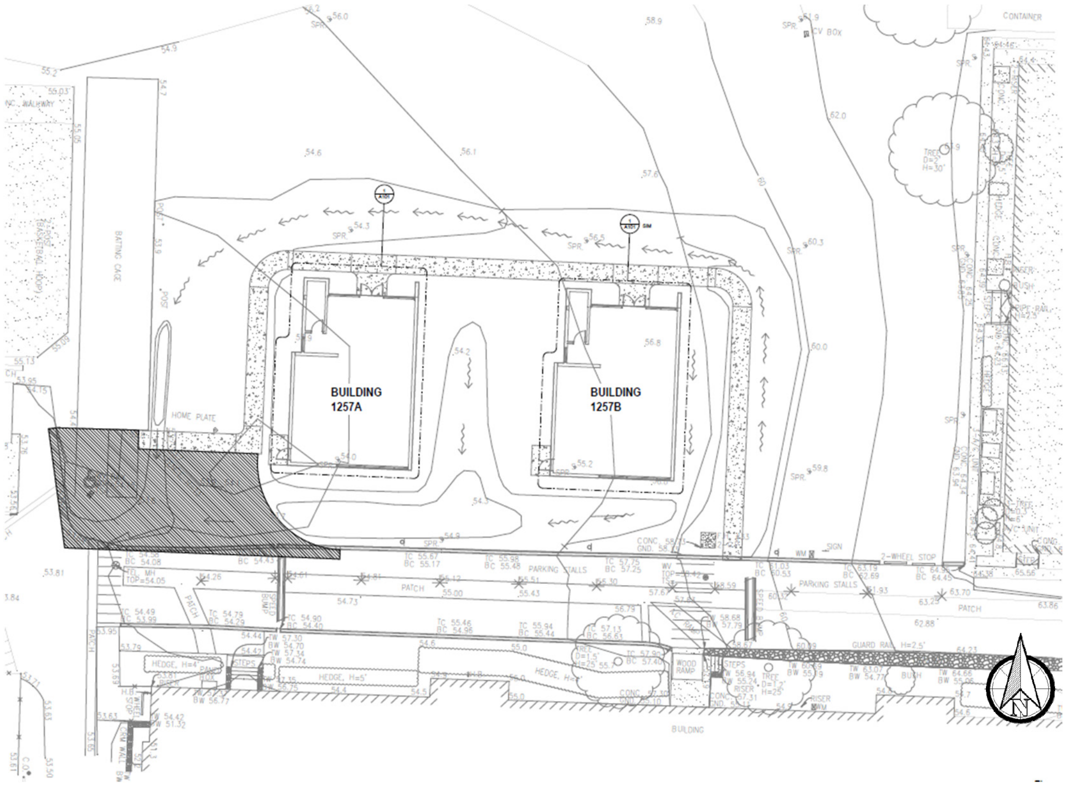


Figure 31. Site Plan
Source: Provided by HNEI

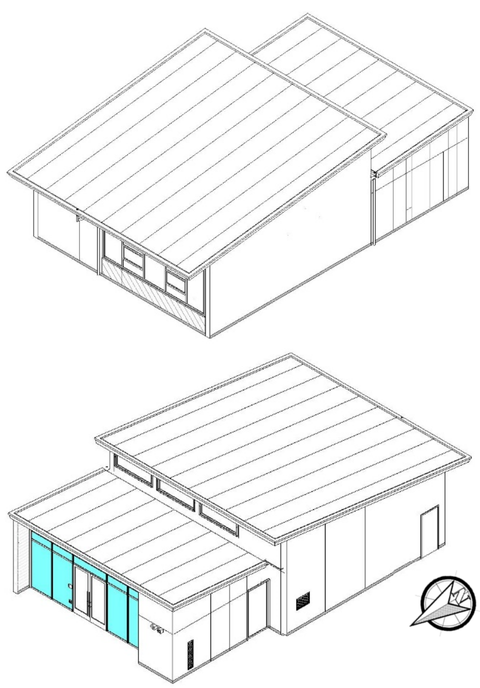


Figure 32. 3D isometric view of Frog building
Source: Provided by HNEI

Outline Information:

Owner/Client:	University of Hawaiʻi at Mānoa
Project Sponsor:	UHM Hawaiʻi Natural Energy Institute
Climate Zone:	Hot & humid (1A)
Weather File Location:	Honolulu Int AP
Occupant Schedule:	Mon – Fri (8am – 5pm)
Occupancy Type:	College Education Classroom
Stories:	Single Stories
Gross Area:	~1513 SF
Occupant Load:	75 Occupants (1,513sq.ft/20 sq.ft per occupant)
Overall Dimensions:	Approximately 40' wide x 87.5' long, 14' to 20' high
HVAC System:	Split HVAC

Air-Conditioning Load parameters	(Based on ASHRAE Design conditions for Honolulu, Hawaii)
Outdoor design:	88.7°F DB, 73.5°F WB
Indoor design:	75°F DB, 55% RH ±5%

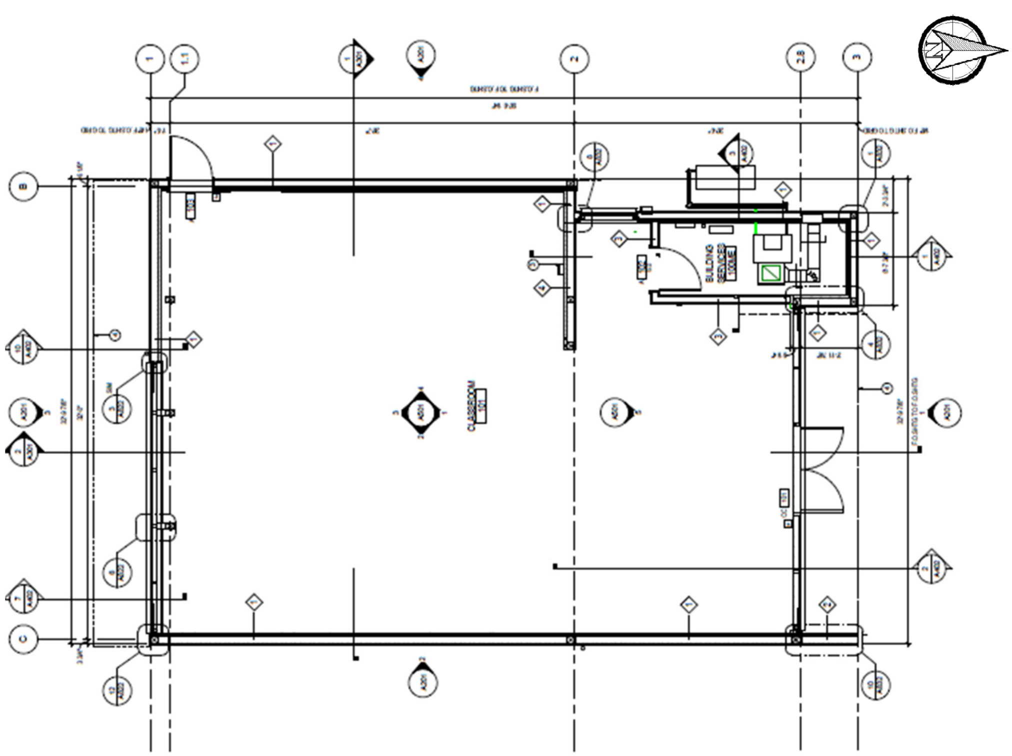


Figure 33. Floor plan
Source: Provided by HNEI

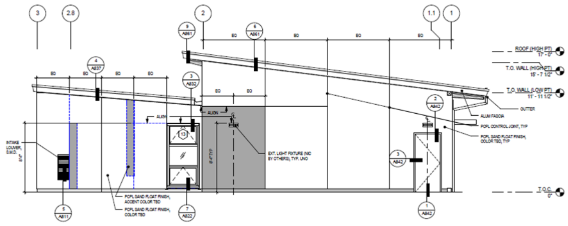


Figure 34. Exterior elevation – West
Source: Provided by HNEI

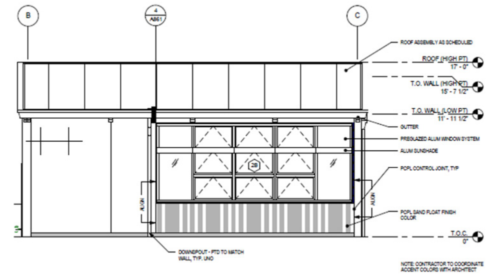


Figure 35. Exterior Elevation – South
Source: Provided by HNEI

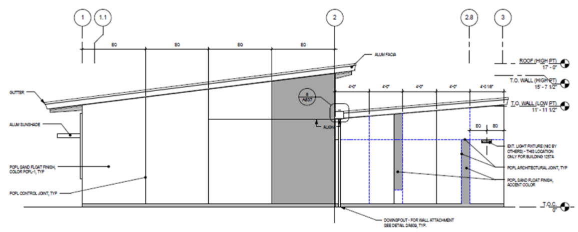


Figure 36. Exterior elevation – East
Source: Provided by HNEI

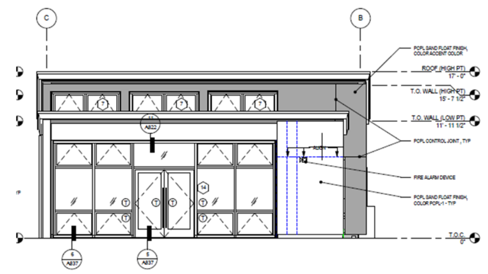


Figure 37. Exterior Elevation – North
Source: Provided by HNEI

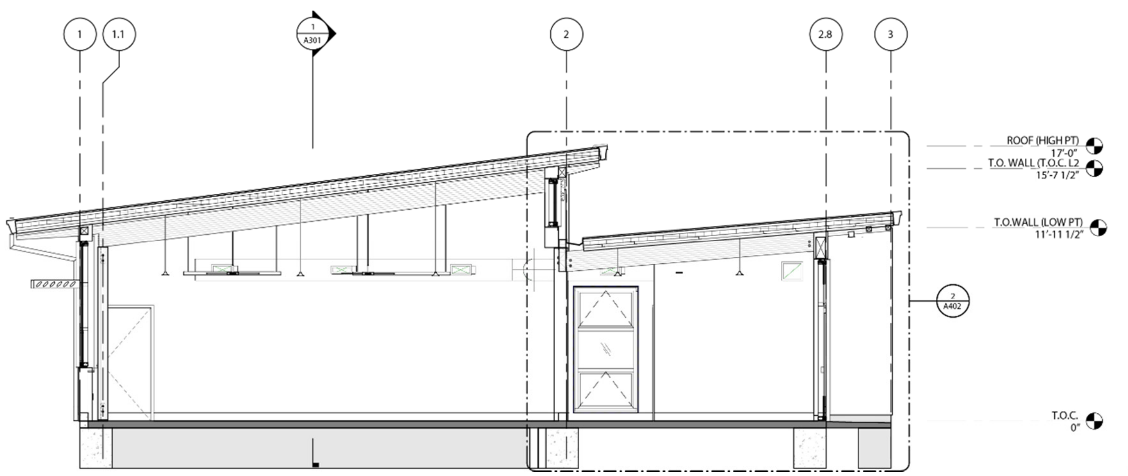


Figure 38. Building section – Longitudinal
Source: Provided by HNEI

8.4 Energy Model Criteria

The goal of energy modeling is to accurately predict the energy use of a building to either test the energy performance of the building in regard to an established standard, or to compare and contrast two buildings in order to find the resulting energy savings. It is important to establish energy model criteria before diving into the energy model itself; the purpose of the criteria is to establish a standard for the baseline for comparison purposes. The baseline model provides information that is used to monitor and assess the effectiveness of new implementations in the building. This project assesses the performance of one of the Frog buildings, henceforth referred to as the Frog building, based on three different envelope assemblies and two future climate conditions using simulated future EPW weather data in BES program under the A2 scenario.

Table 17 displays the specification of the envelope construction for each of the three energy models. The purpose of this matrix is to establish the standard of each energy model and to identify each model's envelope design for energy performance comparisons. The research identifies which building envelope design is optimum and how this proposed envelope assembly will react to climate change condition predictions for 2050 and 2080.

The first energy model is based on the mechanical, electrical, and envelope assembly specifications of the Frog building's design and is referred to as the Current Design model. The second energy model is based on the ASHRAE 90.1-2010 Standard for building performance and is referred to as the ASHRAE 90.1-2010 Design model. The final energy model was designed for this project based on the results obtained from the envelope sensitivity study conducted on the ASHRAE 90.1-2010 Design model (detailed in chapter 14) for the purpose of identifying an optimal envelope design for the Frog building and is referred to as the Proposed Design model.

Table 17. Energy Model Matrix

	DESCRIPTION	CURRENT DESIGN	ASHRAE 90.1 2010 DESIGN	PROPOSED DESIGN
ENVELOPE	Exterior Wall Construction - Wood frame construction	R-21 Insulation U-value 0.044 Btu/hr-sqft °F	R-13 Insulation U-value 0.089 Btu/hr-sqft °F	R-35 Insulation U-value 0.029 Btu/hr-sqft °F
	Roof Construction - Steel Frame	R-29 Insulation U-value 0.034 Btu/hr-sqft °F SRI-0.82	R-19 Insulation U-value 0.065 Btu/hr-sqft °F SRI-0.64	R-65 Insulation U-value 0.018 Btu/hr-sqft °F SRI-0.82
	Window Glazing	U-value 0.25 Btu/hr-sqft °F SHGC-0.265	U-value 1. Btu/hr-sqft °F SHGC-0.25	U-value 0.15 Btu/hr-sqft °F SHGC-0.15
MECHANICAL	Seasonal Energy Efficiency Ratio (SEER)	13 SEER	13 SEER	13 SEER
ELECTRICAL	Lighting Power Density (LDP) (W/ft^2)	Classroom - 0.4 (W/ft^2) Storage - 0.4 (W/ft^2) -No Daylight Sensor -No Occupancy Sensor	Classroom - 0.99 (W/ft^2) Storage - 0.63 (W/ft^2) -No Daylight Sensor -No Occupancy Sensor	Classroom - 0.4 (W/ft^2) Storage - 0.4 (W/ft^2) -No Daylight Sensor -No Occupancy Sensor
	MISC. EQUIPMENT OFFICE EQUIPMENT	0.48 (W/ft^2) 0.95 (W/ft^2)	0.48 (W/ft^2) 0.95 (W/ft^2)	0.48 (W/ft^2) 0.95 (W/ft^2)

Chapter 9: Sensitivity Study for Building Envelope Design

Buildings are the single largest end-use energy contributors to global emissions. The increases in energy use in the built environment from HVAC systems alone will result in larger CO_2 emissions, which in turn will further contribute to climate change and global warming, if no significant changes are made. More energy-efficient building designs and operations are necessary to help reduce emissions and lower the energy demand on our planet.

In this study, four potential mitigation measures concerning the building envelope design were considered. The study looked at these four building envelope design variables based on their relatively high-influence coefficients (a measure of how sensitive the building energy use is to changes in the design variables). The four variables are the exterior wall R-value, the roof R-value, the window glazing U-value, and the SHGC. Different values were considered for each design variable in order to identify the most energy-efficient measures.

The Current Design model was chosen as the subject for analysis of the different values of each design variable. The present-day EPW weather data along with the BES program, DesignBuilder, were used to analyze the performance of the building envelope design. The results for this study contributed to the development of the Proposed Design model, a model intended to be more adaptive to climate change than both the Current Design and ASHRAE Design models.

9.1 Wall R-Value

Definition

The R-value is a measure of the thermal resistance for a particular material or assembly of materials (e.g., insulation panels). The R-value is the reciprocal of the thermal conductance, or U-value. The term R-value, used in this section, refers to the thermal resistance of the assembly of the exterior walls. In theory, the higher the R-value, the greater the resistance will be to heat transfer.

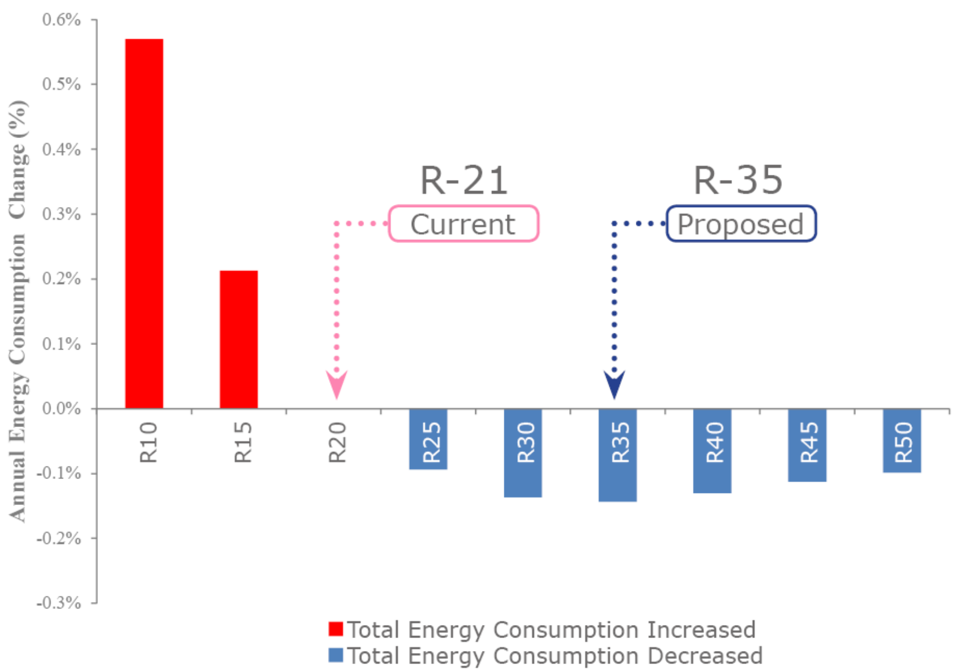


Figure 39. Exterior wall R-value parametric simulation analysis using DesignBuilder.
Source: Author

Result

These simulation runs were conducted to identify the most effective R-value for the exterior wall. Based on the Current Design, R-21 is the recommended value for the exterior wall envelope design. As shown above, any value below R-20 increased the Frog building's energy consumption and any value above R-20 decreased energy consumption. It is important to note, however, that too great of an R-value can reverse the effect. According to the results shown in figure 39, R-35 appears to be the most effective R-value for the Proposed Design model; every value afterward decreased its efficiency.

9.2 Roof R-Value

Definition

The R-value, as defined above, is a measure of the thermal resistance of the particular material or assembly of materials. The R-value is the reciprocal of the thermal conductance, or U-Values. The term R-value used in this section refers to the thermal resistance of the assembly of the roof. Again, in theory, the higher the R-value, the greater the resistance will be to heat transfer.

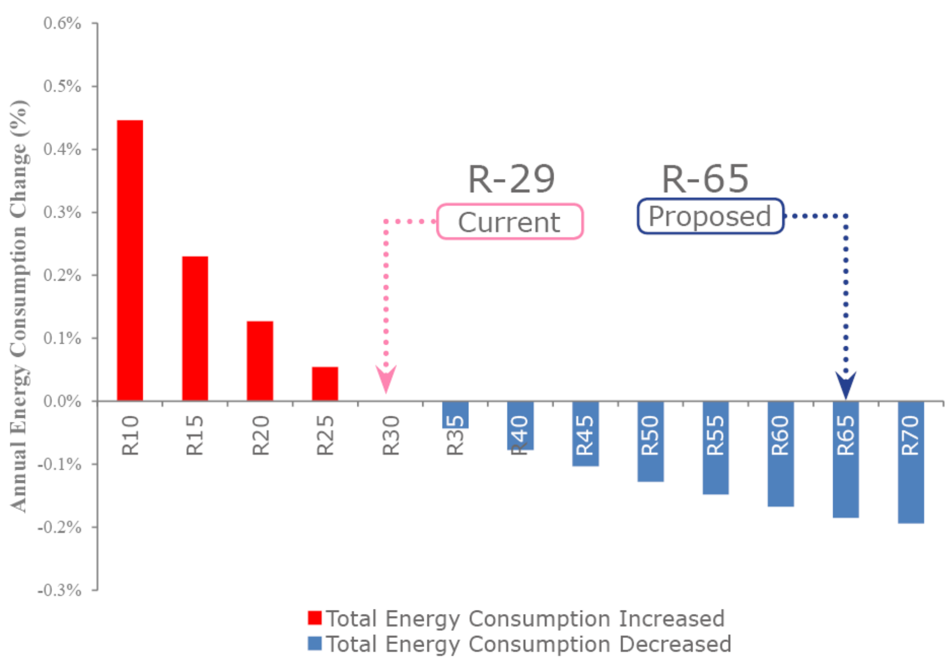


Figure 40. Roof R-value parametric simulation analysis using DesignBuilder.
Source: Author

Result

These simulation runs were conducted to identify the most effective R-value for the roof. Based on the Current Design, R-30 is the recommended value for the roof envelope design. As shown above, any value below R-30 increased the Frog building's energy consumption and any value above R-30 decreased the energy consumption. It is important to note, again, that too great of an R-value can reverse the effect. From the results in figure 40, R-65 appears to be the most effective R-value for the Proposed Design model; every value afterward decreased its efficiency.

9.3 Window Glazing U-Value

Definition

The U-value is used to quantify overall heat flow. For windows, it expresses the total heat transfer coefficient of the system (in Btu/hr-sf-°F) and includes conductive, convective, and radiative heat transfer. The U-value of windows varies primarily based on the number of glazing panels, gases, coatings, and conductivity of window frames. In theory, the lower the U-value, the greater the resistance will be to heat transfer.

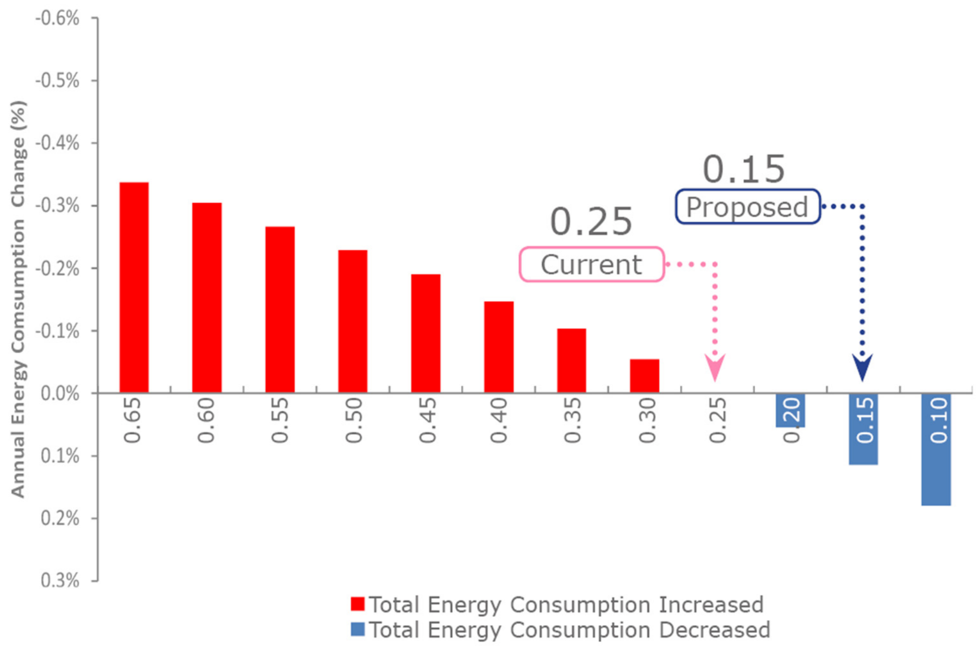


Figure 41. Window glazing U-value parametric simulation analysis using DesignBuilder.
Source: Author

Result

These simulation runs were conducted to identify the most effective U-value for the window glazing. Based on the Current Design, U-0.15 is the recommended value for building's window glazing. As shown above, any values above U-0.25 increased the Frog building's energy consumption and any values below decreased the energy consumption. From the results shown in figure 41, any value below U-0.25 is reasonable. Due to the availability of the product on the US market, U-0.15 was selected for the Proposed Design model; windows with glazing values below U-0.15 might not be as readily available in the US.

9.4 SHGC

Definition

The Solar Heat Gain Coefficient (SHGC) is a fraction of incident solar radiation that directly and indirectly enters through a window assembly as heat gain. SHGC is expressed as a number between 0 and 1. In theory, the lower a window's SHGC, the less solar heat it transmits and the greater its shading ability.

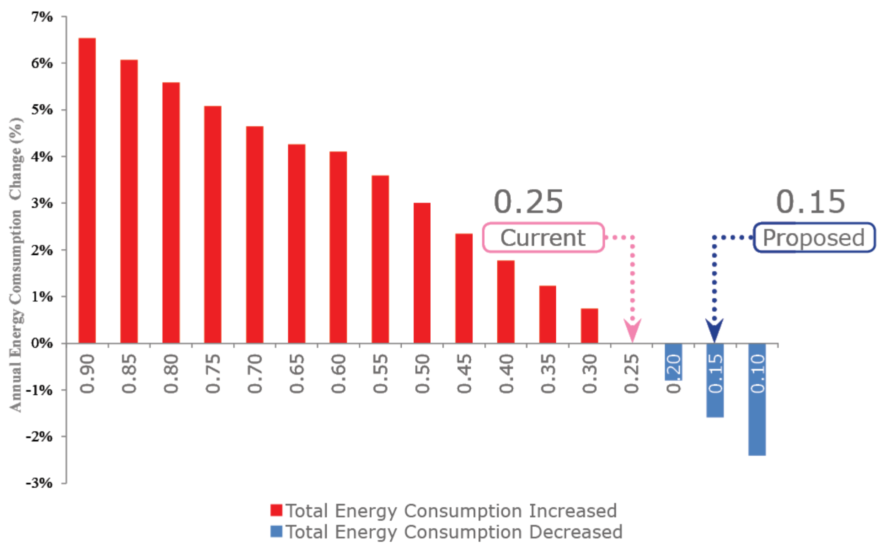


Figure 42. SHGC parametric simulation analysis using DesignBuilder.
Source: Author

Results

These simulation runs were conducted to identify the most effective value for the SHGC. Based on the Current Design, SHGC-0.25 is the recommended value. As shown above, any value above 0.25 increased the Frog building's energy consumption and any value below 0.25 decreased the energy consumption. From the results shown in figure 42, any value below SHGC-0.25 is reasonable. Due to the availability of the product on the

US market, SHGC-0.15 was selected for the Proposed Design model; windows with other values below SHGC-0.15 might not be as readily available in the US.

It is important to note the reason the SHGC's scale is different from the scales of the other design variables. Solar heat gain through windows is one of the largest contributors to building heat gain and energy consumption in hot climate zones. Windows with high SHGC ratings are more effective at collecting solar heat during the winter, while those with low SHGC ratings are more effective at reducing cooling loads during the summer by blocking heat gain from the sun. In essence, the SHGC is important to understand and consider when designing an energy-efficient building.

9.5 Conclusion

Table 18. Annual energy savings from the four envelope components based on the sensitivity study

	Current Design	Proposed Design	Annual Energy Savings
Exterior Wall R-Value	21	35	0.14 %
Roof R-Value	29	65	0.19 %
Window Glazing U-Value	0.25	0.15	0.08 %
SHGC	0.265	0.15	1.58 %

Source: Author

The purpose of this sensitivity study was to develop a greater understanding of building envelope design and how different values can affect a building's performance. In this case, the Current Design model was used for the parametric simulation runs for the four proposed mitigation variables (see table 18). For each parametric simulation run and for each design variable, the analysis process was the same. The analyses are based on the variables' relatively high influence coefficients for quantifying how the building energy use would change when design values are changed. The results for this initial study show potential benefit for understanding the sensitivities of the envelope design variables.

The results of this study identified the most favorable values for the envelope construction, which were then applied to the Proposed Design model. These are: R-35 for the exterior wall with a 0.14% energy reduction; R-65 for the roof with a 0.19% energy reduction; U-0.15 for the window fenestration with a 0.08% energy reduction, and finally 0.15 for the SHGC with a 1.58% energy reduction. The Proposed Design model, according to these results, should achieve an overall 2% reduction in annual energy use for the present-day period.

Chapter 10: Assessment of the Three Design Models under the Predicted A2 Scenario

The 2007 IPCC SRES developed a future climate projections model based on four possible future scenarios of GHG emissions (A1, A2, B1, and B2). These four scenarios explore alternative development pathways, covering a range of demographic, socio-economic, and technologies-driven forces that result in varying levels of GHG emissions. The SRES future projections are widely used in assessments of future climate change. Each of these scenarios describes the relationships between the forces driving GHG and aerosol emissions and their potential evolution through the twenty-first century (see chapter 5 for SRES scenario details).

Meteonorm software allows users to generate three out of the four possible future scenarios: (1) A2 (second highest emissions), (2) A1B (balanced emissions), and (3) B1 (low emissions) (see chapter 7 for details on generating simulated future EPW weather data). Due to time limitations, this research focuses on the A2 scenario. This scenario represents the second highest emissions prediction.

This chapter presents the overall results of the Frog building model simulations in eQuest. The simulations were conducted to measure each of the three models' building energy consumption under the A2 scenario for the three time periods (present-day, 2050, and 2080). The chapter also presents data validating the use of future EPW weather data in eQuest.

The simulation study analyzes the different characteristics of each model's envelope design under the three time periods. Each model was put through a rigorous modeling process using eQuest to create an envelope assembly based on the different criteria of the study. The outcome of these simulation studies helped ascertain some of the potential effects of climate change on the building envelope design.

The eQuest software allowed for manual input of the material properties based on the real product. In this case, the building envelope materials for the Current Design model had to be manually input into the software, see figure 47 - figure 49. This method of energy modeling is tedious but the end result improves the accuracy of the simulation based on the exact material properties.

Other programs have limited libraries of standard material templates. Using such templates is okay for the initial design phase but not for the later phase when designers are seeking to identify the performance of the actual building envelope design. Using eQuest's manual input function, one can specify materials that are not in the library and therefore generate specialized materials specifications based on the products planned for use in the actual design. This portion of the research took many hours to complete, both in the information input and the research of the individual material properties from the manufacturers, including thickness, conductivity, density, and specific heat. See appendix C for material data.

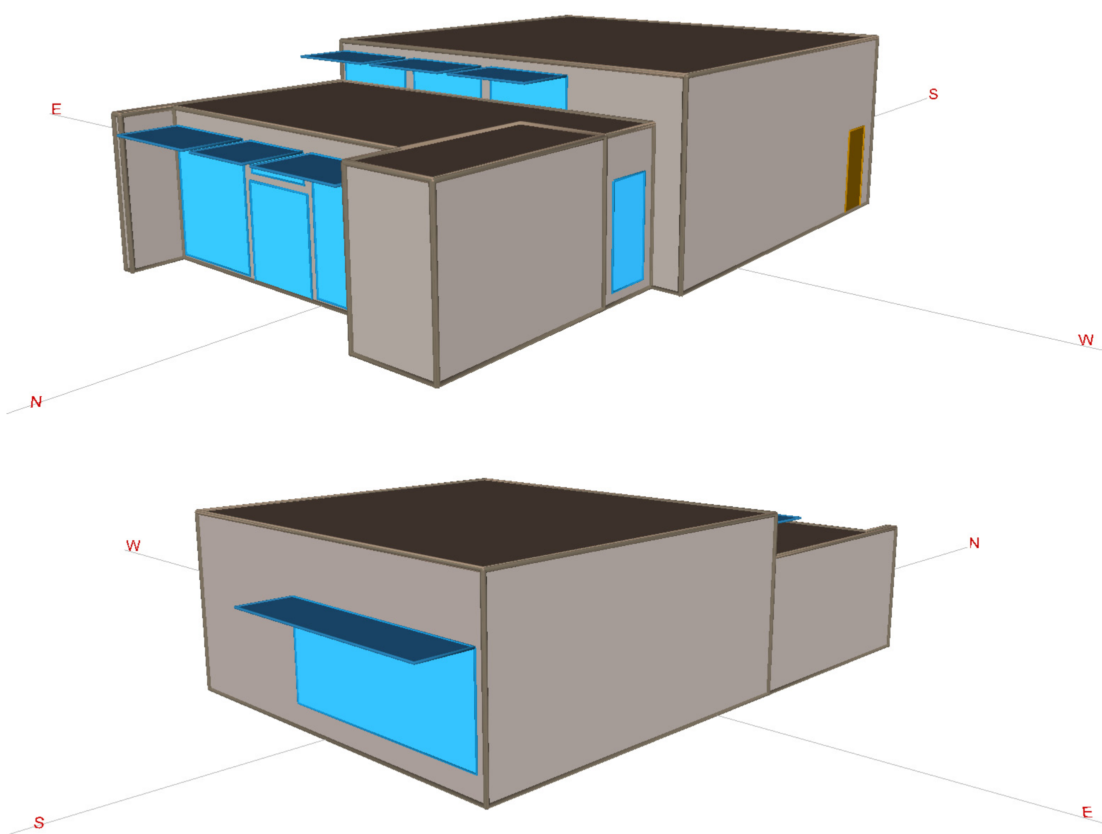


Figure 43. Computer model in eQuest of Frog building
Source: Author

10.1 Current Design Model

Table 19. Current Design model inputs

	Current Design
Exterior Wall Construction	R-21 Insulation U-value 0.044 Btu/hr-sqft °F
Roof Construction	R-29 Insulation U-value 0.034 Btu/hr-sqft °F SRI-0.82
Window Glazing	U-value 0.25 Btu/hr-sqft °F SHGC-0.265
Mechanical	13 SEER
Electrical	Classroom - 0.4 (W/ft^2) Storage - 0.4 (W/ft^2) -No Daylight Sensor -No Occupancy Sensor
Misc. Equip. Office Equip.	0.48 (W/ft^2) 0.95 (W/ft^2)

Source: Author

The first energy model, the Current Design model, was created by inputting the mechanical, electrical, and envelope assembly of the Frog building's original design specifications (see table 19). The design specifications came from the construction document designed by the Frog building architects and mechanical engineers. This first energy model is referred to as the Current Design model. The Current Design model was used, along with the ASHRAE and Proposed Design models, to determine which of the design models would consume the least amount energy in the simulations.

Building Envelope Assembly

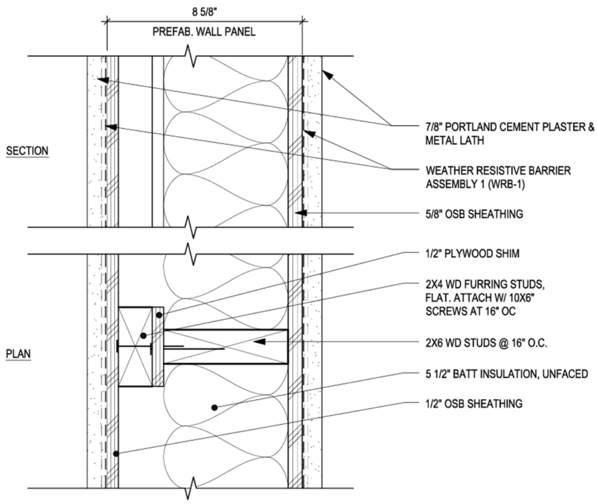


Figure 44. Typical exterior wall construction assembly based on Frog building design
Source: HNEI and UHM

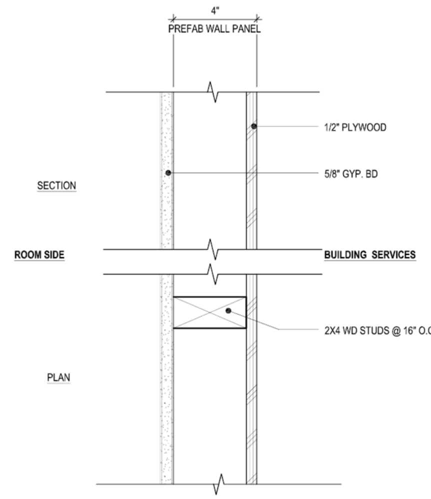


Figure 45. Typical interior wall construction assembly based on Frog building design
Source: HNEI and UHM

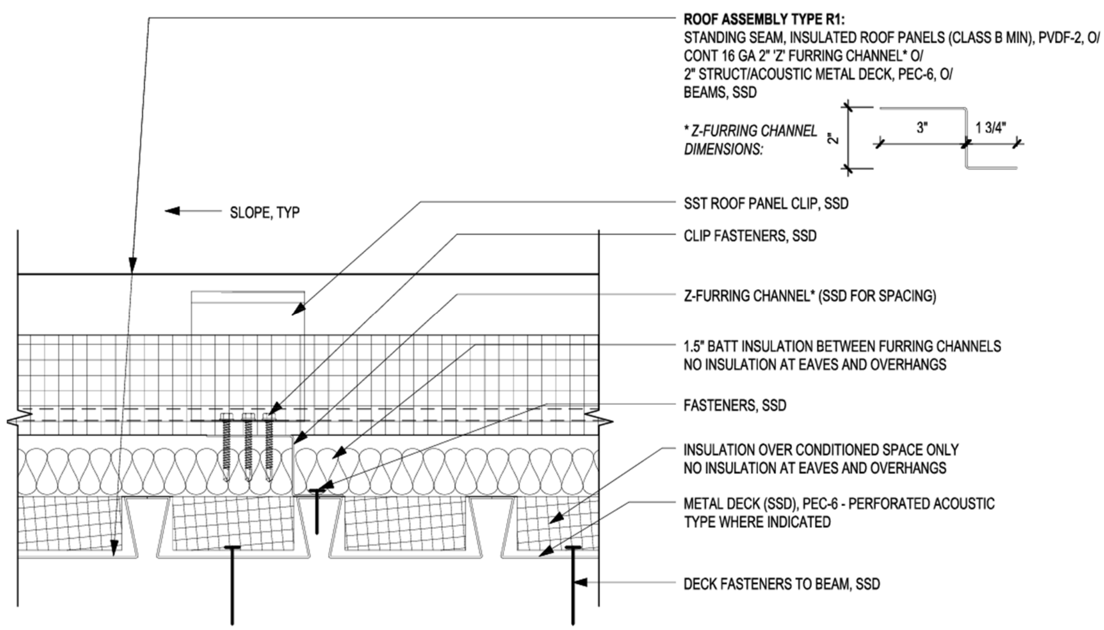


Figure 46. Typical roof construction assembly based on Frog building design
Source: HNEI and UHM

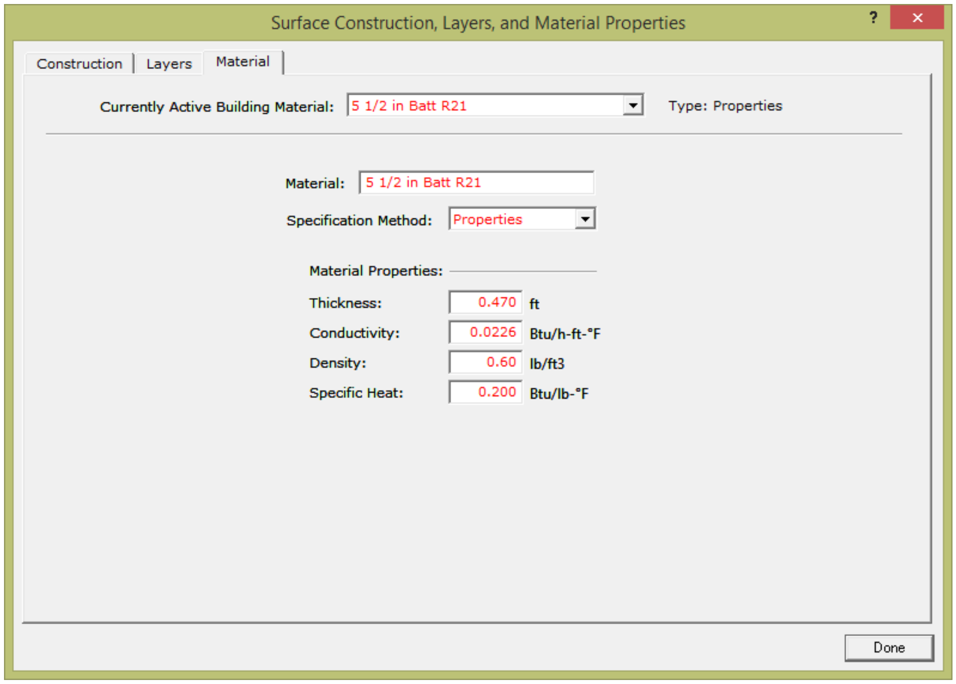


Figure 47. Exterior wall material input for 5 ½” batt insulation (eQuest)
Source: Author

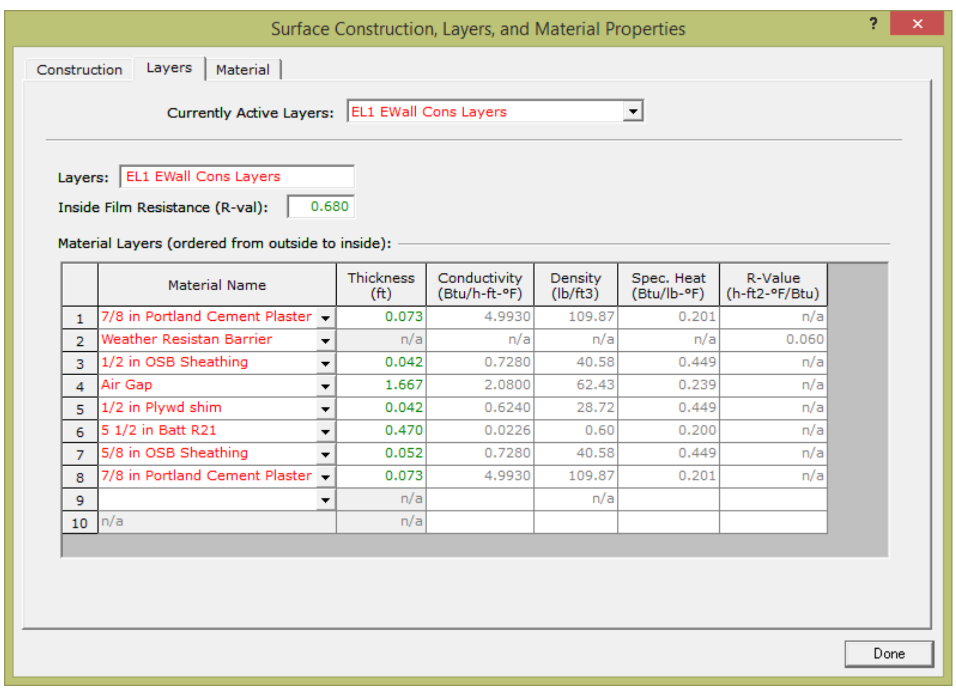


Figure 48. Exterior wall construction assembly layers (eQuest)
Source: Author

To specify the construction characteristics and properties of the exterior wall, the material properties needed to be manually input into eQuest under the material properties function. Figure 47 is a screenshot showing the manual input for the 5 ½" batt insulation material for the Current Design model. Figure 48 shows the overall envelope construction assembly of the exterior wall.

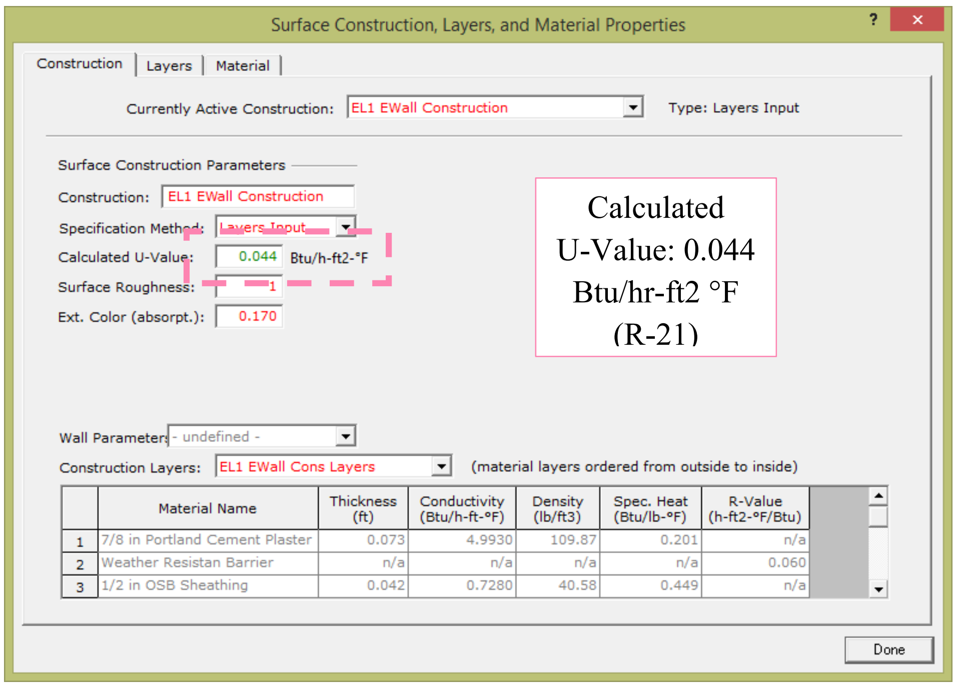


Figure 49. Overall exterior wall construction assembly showing the U-value to be U-0.044 (R-21 insulation) (eQuest)
Source: Author

The Current Design model's building envelope construction, as specified by the construction document, uses R-21 insulation with a U-value of 0.044 for the exterior wall; R-29 insulation with a U-value of 0.034 and an SRI value of 0.82 for the roof; and a U-value of 0.26 and an SHGC of 0.265 for the window glazing. See appendix C for the roof construction assembly.

Impact of Future EPW Weather Data on Building Energy Use Analysis

Figure 50 through figure 52 lay out the simulation results, which show the Current Design model's energy efficiency performance and the impact of future EPW weather data on the building. The model's total annual energy use measured during this simulation run was used to calculate the peak cooling load demand and EUI and, using the future EPW weather data, to determine the model's response to the predicted climate change conditions. The first unit of analysis is the annual EUI, followed by the annual peak cooling load demand, and the annual energy consumption by end use.

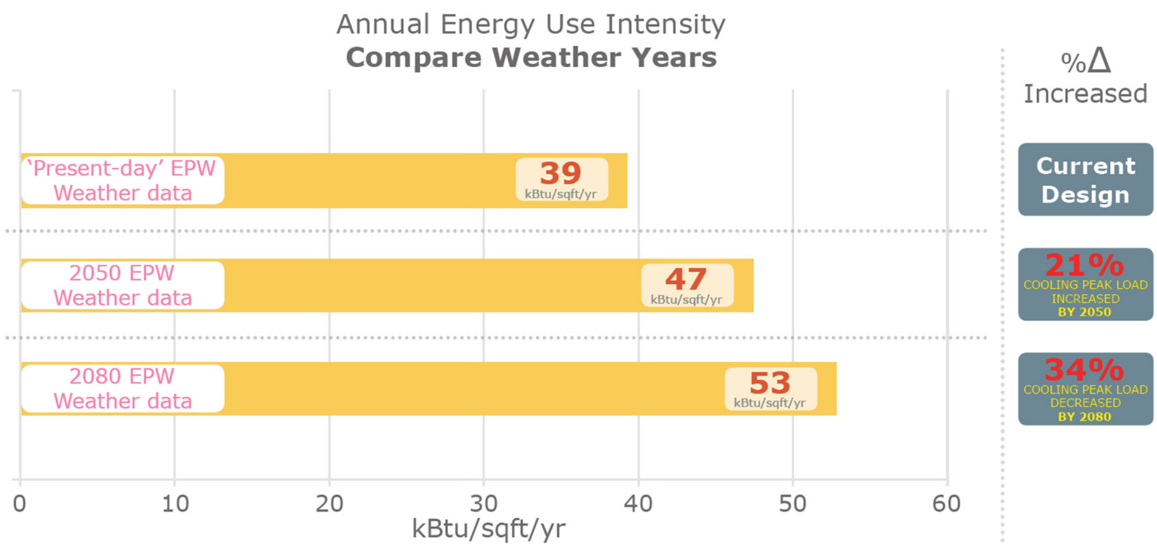


Figure 50. Annual EUI and impact of future EPW weather data (2050 and 2080) on the Current Design model's energy use
Source: Author

A building's energy use intensity (EUI) provides valuable energy performance metrics for the design energy modeling and assessment of building energy performance. The EUI is expressed as energy per square foot per year. It is calculated by dividing the total energy consumed by the building in one year (measured in kBtu) by the total gross floor area of the building. Generally, a low EUI signifies good energy performance.

Based on the simulation results for the present-day EPW weather data, the Current Design model's EUI was 39 kBtu/sqft/yr. The model's EUI in 2050 increased by

8 kBtu/sqft/yr (21%) and in 2080, by 6 kBtu/sqft/yr for an overall increase of 34% across all time periods.

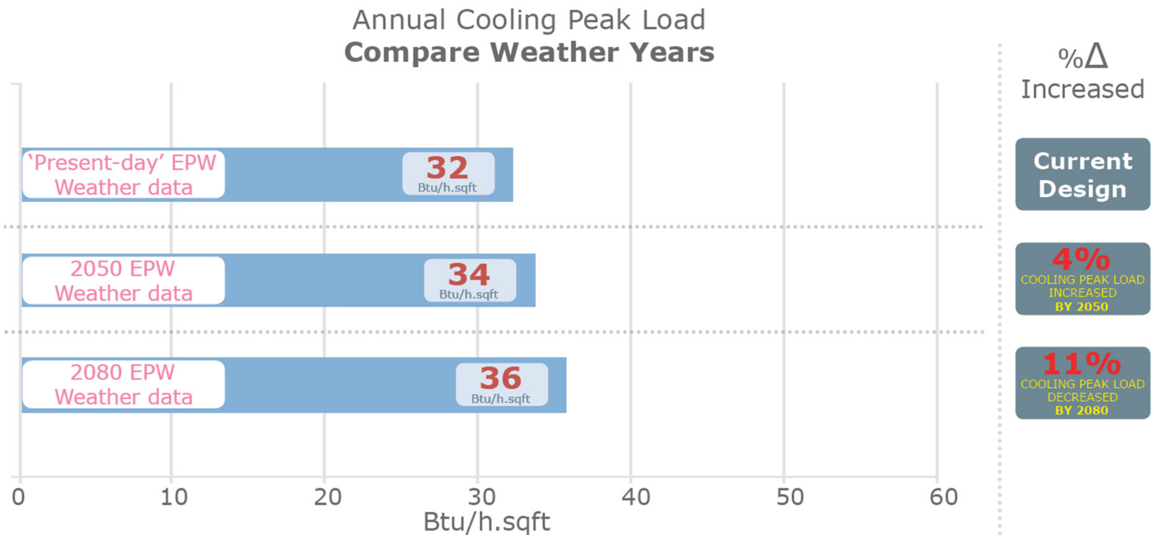


Figure 51. Annual peak cooling load and impact of future EPW weather data (2050 and 2080) for the Current Design model's energy use
Source: Author

Peak cooling load is used for sizing HVAC equipment in order to provide adequate heating or cooling under extreme weather conditions. In the case of the Frog building, the focus is on the cooling load due to Hawai'i''s hot and humid climate.

Based on the simulation results for the present-day EPW weather data, the Current Design model's annual peak cooling load was 32 Btu/h.sqft. The model showed a 2 Btu/h.sqft (4%) increase in 2050 and in 2080, another 2 Btu/h.sqft for an overall 11% increase across all time periods.

Table 20. Energy consumption in Current Design model by end use

Energy End Use	Present-day (kWh)	2050 (kWh)	2080 (kWh)
Ventilation Fan	2,186	2,186	2,186
Miscellaneous Equipment	4,176	4,176	4,176
Area Lightings	1,310	1,310	1,310
Space Cooling	8,615	11,975	14,224

Source: Author

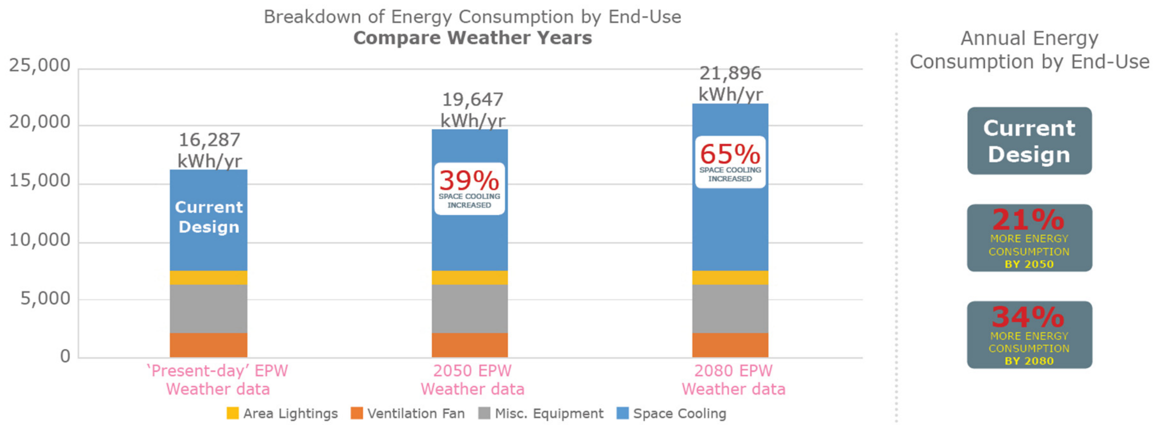


Figure 52. Annual energy consumption by end use and impact of future EPW weather data (2050 and 2080) for the Current Design model's energy use
Source: Author

Figure 52 shows the simulation results of the Current Design model's annual consumption by end use for each time period. The Current Design model's annual energy consumption by end use was 16,287 kWh. In 2050, a 3,360 kWh (21%) increase was measured and in 2080, another 2,249 kWh increase was measured for an overall 34% increase across all time periods.

Table 20, a breakdown of the model's annual energy consumption by end use in each time period, shows that the largest amount of energy use was from the annual space cooling of the HVAC system, which accounted for half of the total annual energy use (8,615 kWh), followed by miscellaneous equipment (4,176 kWh), ventilation fans (2,186 kWh), and area lighting (1,310 kWh). In 2050, the annual space cooling increased to 11,975 kWh, a 39% increase from the present-day time period. In 2080, the annual space cooling increased to 14,224 kWh, a 65% increase from the present-day time period.

10.2 ASHRAE Design Model

Table 21. ASHRAE Design model inputs

	ASHRAE Design
Exterior Wall Construction	R-13 Insulation U-value 0.089 Btu/hr-sqft °F
Roof Construction	R-19 Insulation U-value 0.065 Btu/hr-sqft °F SRI-0.64
Window Glazing	U-value 1.09 Btu/hr-sqft °F SHGC-0.25
Mechanical	13 SEER
Electrical	Classroom - 0.99 (W/ft^2) Storage - 0.63 (W/ft^2) -No Daylight Sensor -No Occupancy Sensor
Misc. Equip.	0.48 (W/ft^2)
Office Equip.	0.95 (W/ft^2)

Source: Author

The second energy model is based on the ASHRAE 90.1-2010 minimum standards for building performance and is referred to as the ASHRAE Design model. The differences between the ASHRAE Design model and the Current Design model lie in the envelope construction assembly and the electrical system input.

The ASHRAE Design model criteria for the Frog building followed the minimum ASHRAE 90.1-2010 design standards for envelope construction, and mechanical and electrical system input. Compared to the envelope construction of the Current Design model, the ASHRAE value requirements for the envelope construction are much lower. Surprisingly, however, the electrical system input for lighting is very high; the ASHRAE standard for lighting density power (LDP) is 0.99 W/ft^2 while the Current Design model required only 0.4 W/ft^2.

The ASHRAE 90.1-2010 Standard was developed to provide minimum energy efficiency requirements for the design and new construction of most buildings and their systems. The Standard is a useful tool for architects and engineers. These requirements include the building envelope construction, the HVAC system, lighting, and miscellaneous equipment.

For this project, the ASHRAE 90.1-2010 Standard was used to develop to ASHRAE Design model. This model was used along with the Current and Proposed

Design models for a comparative study that quantified the energy differences between the minimum requirements, the actual build, and the proposed model.

Building Envelope Assembly

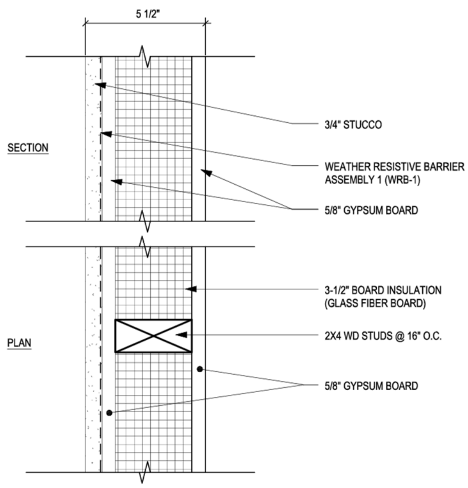


Figure 53. Typical exterior wall construction assembly based on ASHRAE 90.1-2010 minimum standards
Source: Author

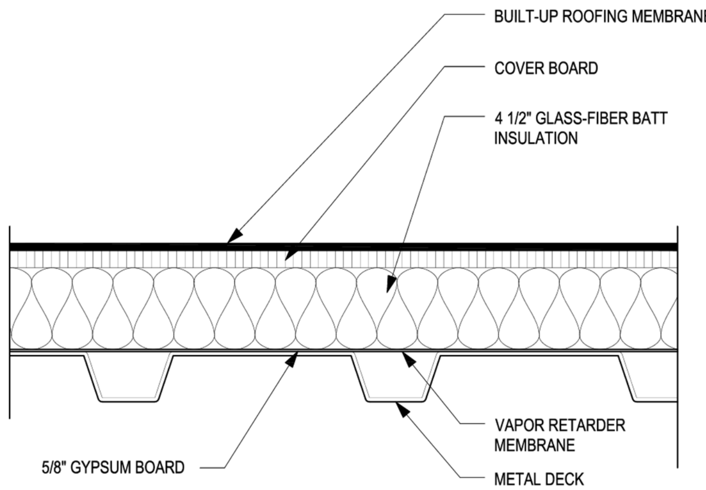


Figure 54. Typical roof construction assembly based on ASHRAE 90.1-2010 minimum standards
Source: Author

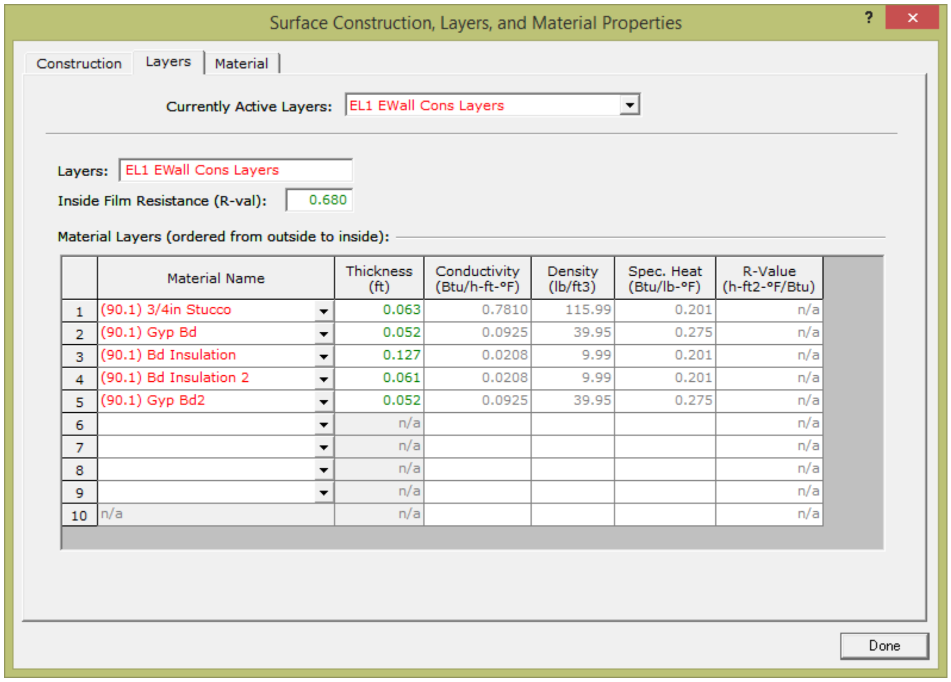


Figure 55. Exterior wall construction assembly layers (eQuest)
Source: Author

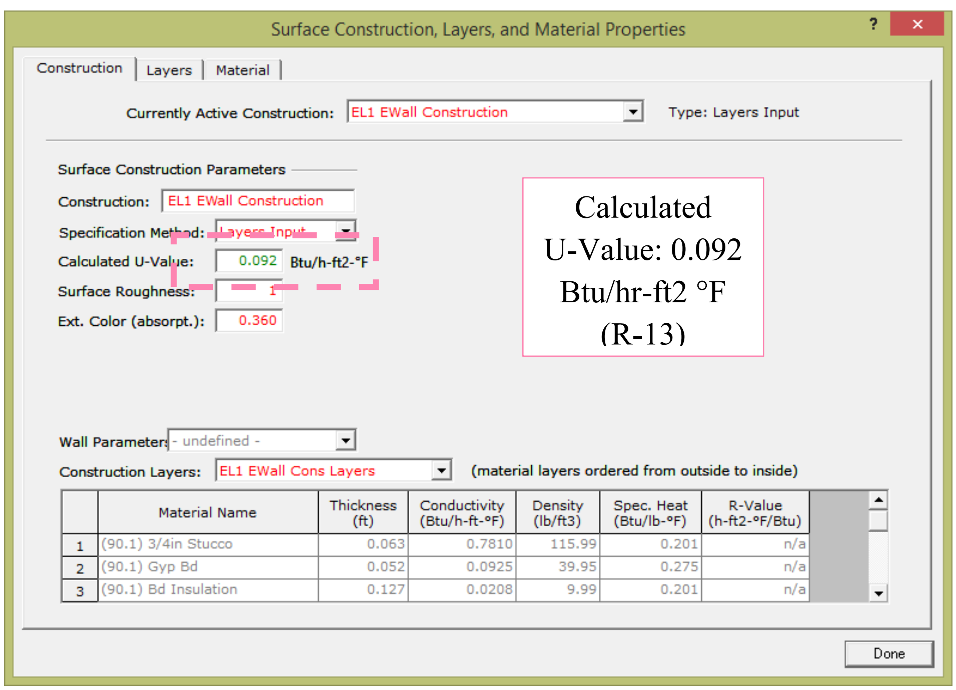


Figure 56. Overall exterior wall construction assembly showing the U-value to be U-0.092 (R-13) (eQuest)
Source: Author

The building envelope assembly for the ASHRAE Design model follows the guidelines laid out in the ASHRAE 90.1-2010 Standard, a document specifying minimum standard requirements for building envelope construction. Based on the envelope construction matrix shown in table 21, the R-value for the exterior wall design is R-13 insulation with an overall U-value of 0.089. The R-value for the roof design is R-19 insulation with an overall U-value of 0.065. The U-value for the window glazing is U-1.09 with SHGC-0.25.

The envelope design for the ASHRAE Design model was established based on these requirements; all specifications were then manually input into eQuest for analysis. The results of this analysis along with the results for the Current Design and Proposed Design models were then used for the comparative study. The results of this comparison quantify the improvements of the Proposed Design model over the other two models. See appendix D for the roof construction assembly

Impact of Future EPW Weather Data on Building Energy Use Analysis

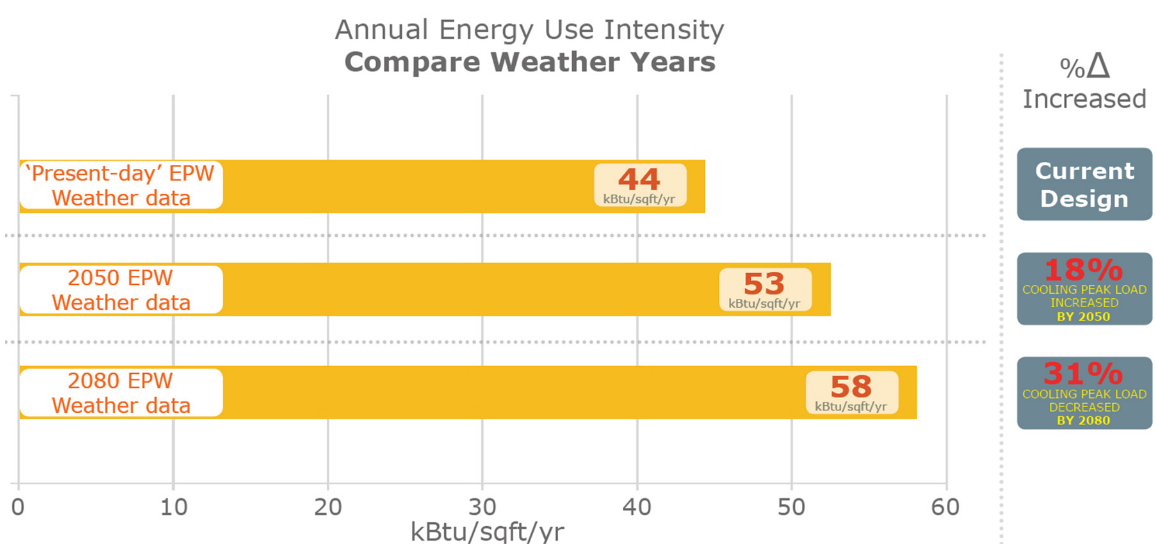


Figure 57. Annual EUI and impact of future EPW weather data (2050 and 2080) for the ASHRAE Design model's energy use
Source: Author

Based on the simulation results for the present-day EPW weather data, the EUI for the ASHRAE Design model was 44 kBtu/sqft/yr. With the use of the 2050 EPW weather data, a 9 kBtu/sqft/yr (18%) increase was measured for 2050. By 2080, the measured EUI increase was 14 kBtu/sqft/yr (31%).

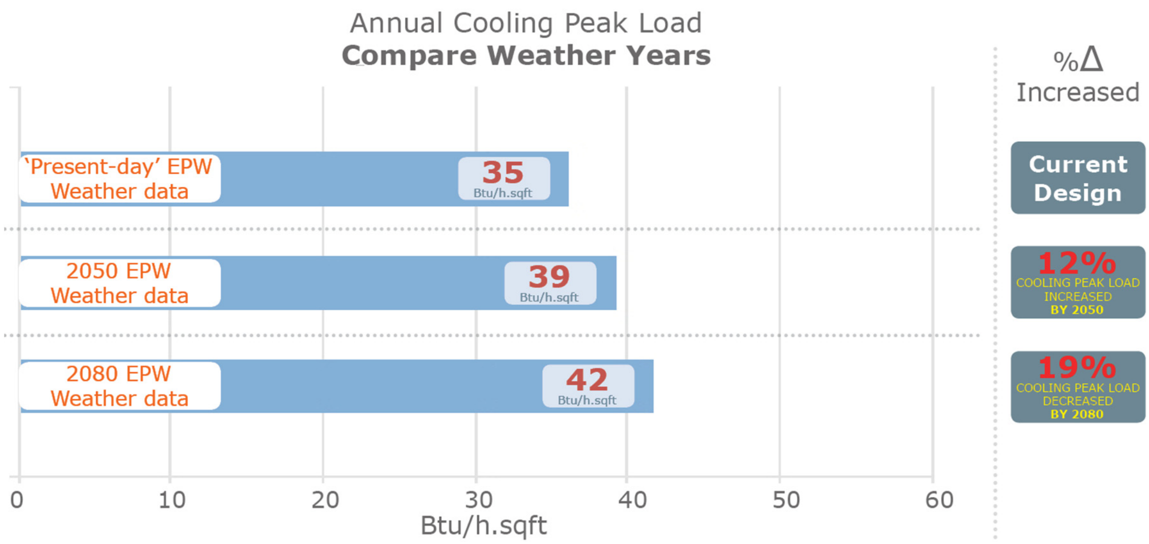


Figure 58. Annual peak cooling load and impact of future EPW weather data (2050 and 2080) for the ASHRAE Design model's energy use
Source: Author

Based on the simulation results for the present-day EPW weather data, the annual peak cooling load demand for the ASHRAE Design model was 35 Btu/h.sqft. With the use of the 2050 EPW weather data, a 4 Btu/h.sqft (12%) increase was measured for 2050. By 2080, the measured increase was 7 Btu/h.sqft (19%).

Table 22. Energy consumption in ASHRAE Design model by end use

Energy End Use	Present-day (kWh)	2050 (kWh)	2080 (kWh)
Ventilation Fan	2,186	2,186	2,186
Miscellaneous Equipment	4,176	4,176	4,176
Area Lightings	3,170	3,170	3,170
Space Cooling	8,879	12,237	14,559

Source: Author

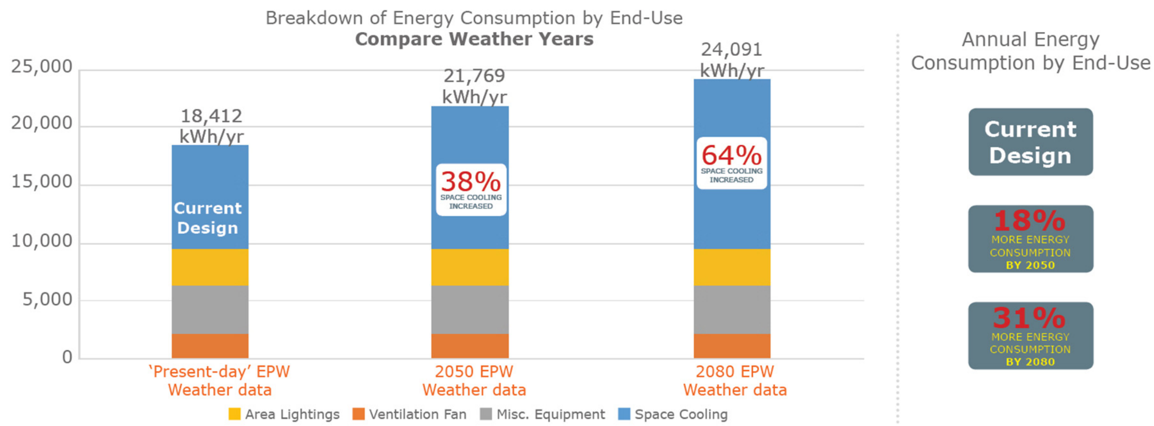


Figure 59. Annual energy consumption by end use and impact of future EPW weather data (2050 and 2080) for the ASHRAE Design model's energy use
Source: Author

Based on the simulation results for the present-day EPW weather data, the annual energy consumption by end use for the ASHRAE Design model was 18,412 kWh. A 3,357 kWh (18%) increase was measured for 2050 and a 5,679 kWh (31%) increase was measure for 2080.

The breakdown of the model's annual energy consumption by end use and the results from the present-day EPW weather data show that the largest amount of energy use was from the HVAC system's annual space cooling use, which accounted for half of the total annual energy usage (8,879kWh), followed by miscellaneous equipment (4,176 kWh), ventilation fans (2,186 kWh), and area lighting (3,170 kWh). In 2050, the annual space cooling increased to 12,237 kWh, a 38% increase from the present-day time period. In 2080, the annual space cooling increased to 14,559 kWh, a 64% increase from the present-day time period.

10.3 Proposed Design Model

Table 23. Proposed Design model inputs

	Proposed Design
Exterior Wall Construction	R-35 Insulation U-value 0.029 Btu/hr-sqft °F
Roof Construction	R-65 Insulation U-value 0.018 Btu/hr-sqft °F SRI-0.82
Window Glazing	U-value 0.15 Btu/hr-sqft °F SHGC-0.15
Mechanical	13 SEER
Electrical	Classroom - 0.4 (W/ft^2) Storage - 0.4 (W/ft^2) -No Daylight Sensor -No Occupancy Sensor
Misc. Equip. Office Equip.	0.48 (W/ft^2) 0.95 (W/ft^2)

Source: Author

The Proposed Design model was created based on the results of the sensitivity simulation study (see chapter 9). The purpose of this study was to develop an understanding of building envelope design and how different values affect how a building performs. I hypothesized that the Proposed Design model would perform better than the Current Design model due to the higher insulation values of its envelope construction.

The Current Design model was the subject for the sensitivity simulation study, which focused on four proposed envelope criteria—exterior wall, roof, window glazing, and SHGC. The simulation runs relied on the relatively high influence coefficients of each criterion to determine how the building energy use would respond when the envelope design values were changed. Different values were considered for each design variable in order to identify the most favorable energy-efficient measures.

Based on the simulation analysis, the most energy-efficient and cost-effective envelope assembly is R-35 (0.14% energy reduction) for exterior walls, R-65 (0.19% energy reduction) for roof, U-0.15 (0.08% energy reduction) for windows, and 0.15 (1.58% energy reduction) for the SHGC. The Proposed Design model, according to these results, will thus consume 2% less total energy than the Current Design model.

Building Envelope Assembly

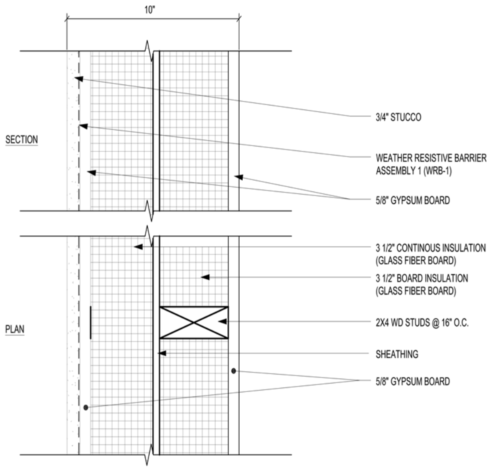


Figure 60. Typical exterior wall construction assembly based on sensitivity study
Source: Author

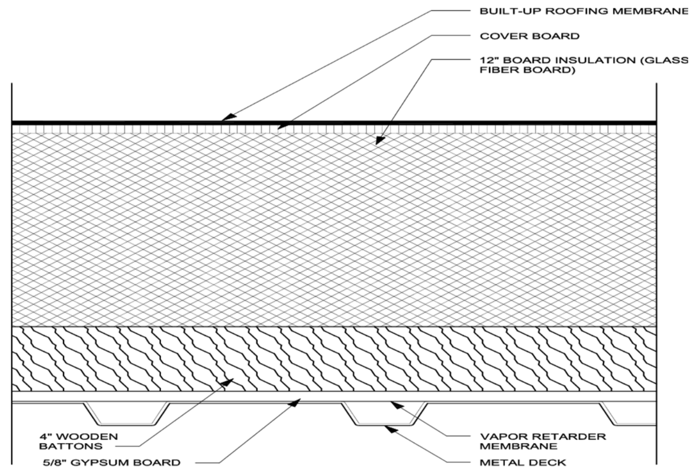
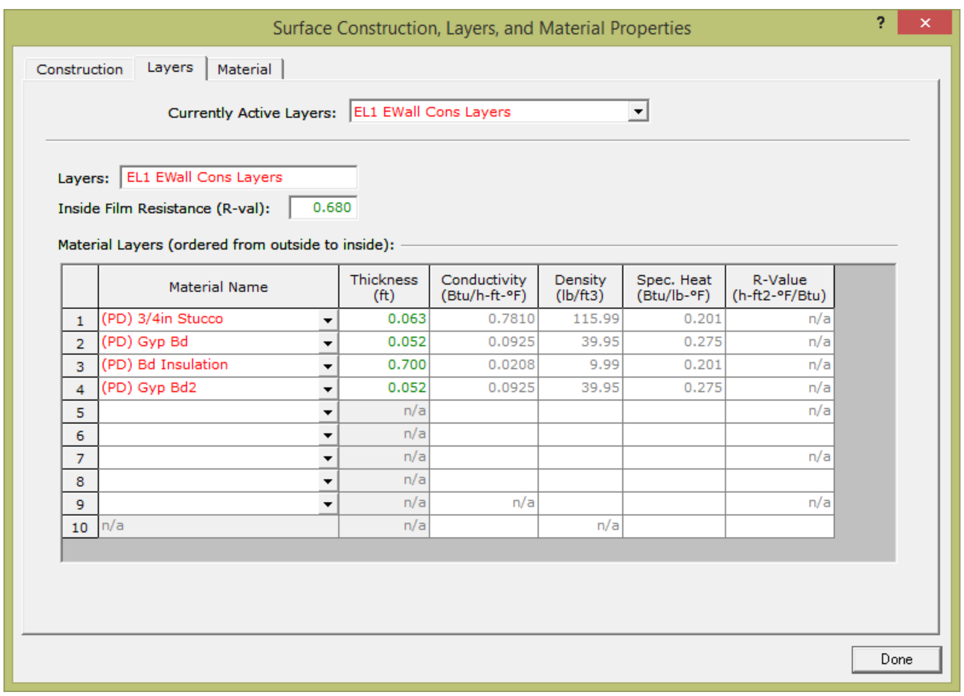


Figure 61. Typical roof construction assembly based on sensitivity study
Source: Author



Surface Construction, Layers, and Material Properties

Construction | Layers | Material

Currently Active Layers: EL1 EWall Cons Layers

Layers: EL1 EWall Cons Layers

Inside Film Resistance (R-val): 0.680

Material Layers (ordered from outside to inside):

	Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
1	(PD) 3/4in Stucco	0.063	0.7810	115.99	0.201	n/a
2	(PD) Gyp Bd	0.052	0.0925	39.95	0.275	n/a
3	(PD) Bd Insulation	0.700	0.0208	9.99	0.201	n/a
4	(PD) Gyp Bd2	0.052	0.0925	39.95	0.275	n/a
5		n/a				n/a
6		n/a				
7		n/a				n/a
8		n/a				
9		n/a	n/a			n/a
10	n/a	n/a		n/a		

Done

Figure 62. Exterior wall construction assembly layers (eQuest)
Source: Author

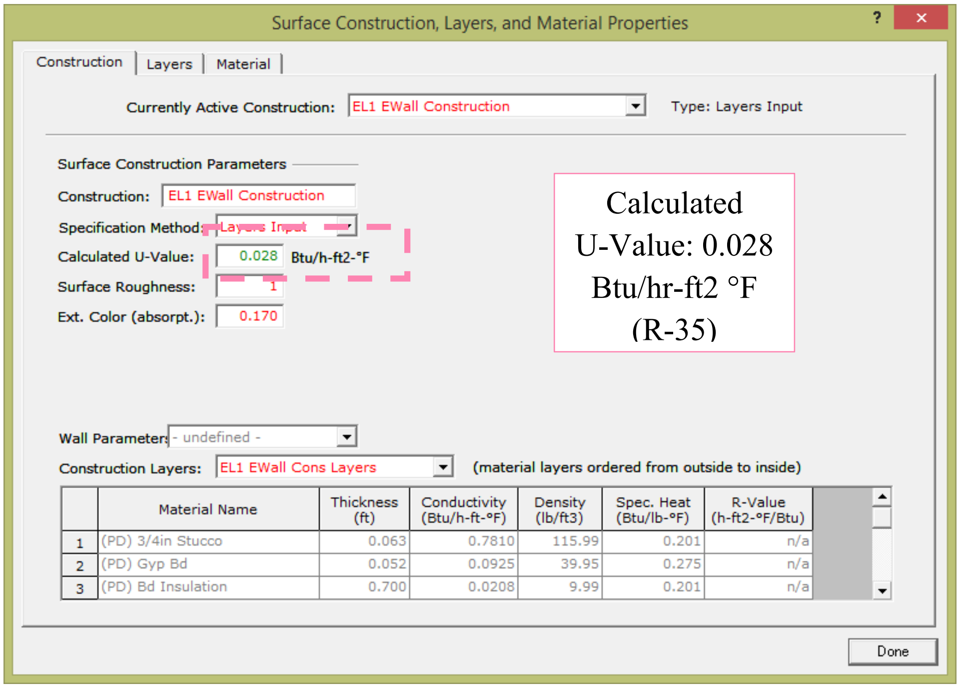


Figure 63. Overall exterior wall construction assembly showing the U-value to be U-0.028 (R-35) (eQuest)
Source: Author

The building envelope inputs for the Proposed Design model, based on the results from the sensitivity study, are: R-35 with a U-value of 0.029 for the exterior wall; R-65 with a U-value of 0.018 for the roof; and a U-value of 0.15 and an SHGC of 0.15 for the window glazing.

The Proposed Design model's envelope specifications were manually input into eQuest for analysis. This model, as explained in previous sections, was then compared to the Current Design and ASHRAE Design models. See appendix E for the roof construction assembly.

Impact of Future EPW Weather Data on Building Energy Use Analysis

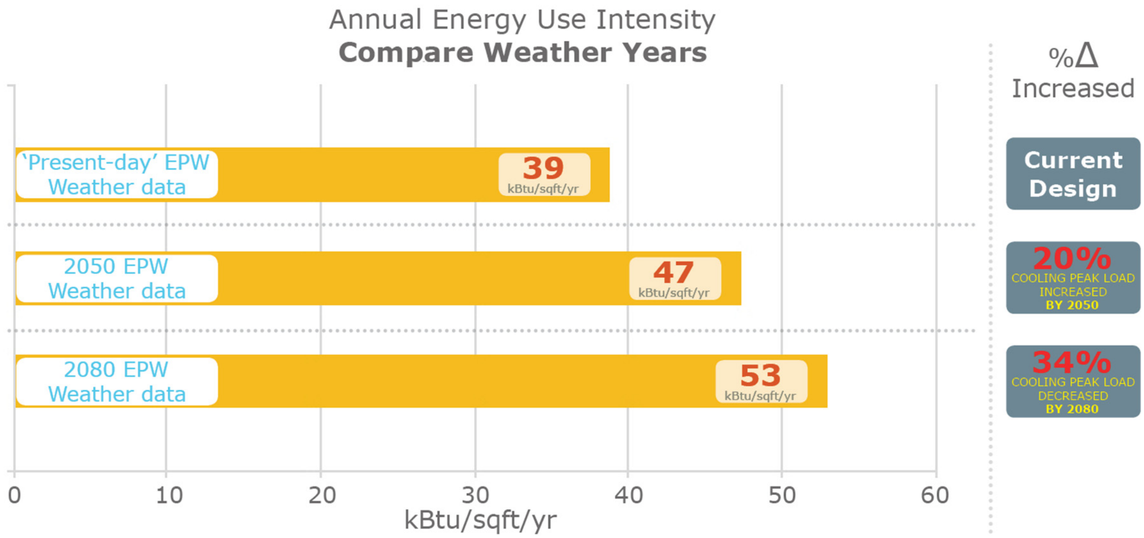


Figure 64. Annual EUI and impact of future EPW weather data (2050 and 2080) for the Proposed Design model's energy use
Source: Author

Based on the simulation results for the present-day EPW weather data, the EUI for the Proposed Design model was 39 kBtu/sqft/yr. With the use of the 2050 EPW weather data, an 8 kBtu/sqft/yr (20%) increase was measured for 2050. By 2080, the measured annual EUI increase was 14 kBtu/sqft/yr (34%).

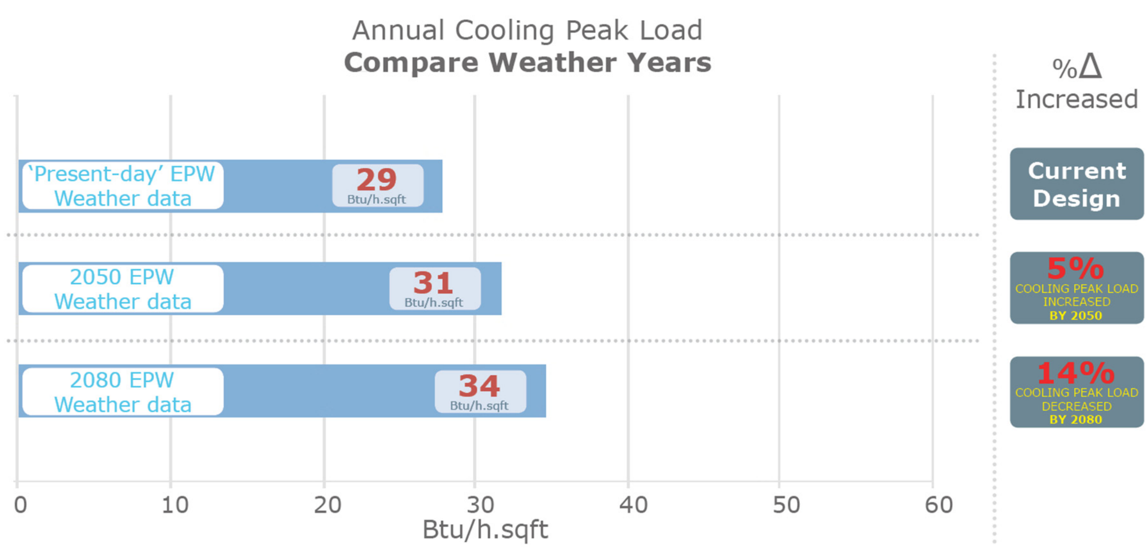


Figure 65. Annual peak cooling load and impact of future EPW weather data (2050 and 2080) for the Proposed Design model's energy use
Source: Author

Based on the simulation results for the present-day EPW weather data, the annual peak cooling load demand for the Proposed Design model was 29 Btu/h.sqft. In 2050, a 2 Btu/h.sqft (5%) increase was measured. By 2080, the measured annual peak cooling load increase was 5 Btu/h.sqft (14%).

Table 24. Energy consumption in Proposed Design model by end use

Energy End Use	Present-day (kWh)	2050 (kWh)	2080 (kWh)
Ventilation Fan	2,186	2,186	2,186
Miscellaneous Equipment	4,176	4,176	4,176
Area Lightings	1,310	1,310	1,310
Space Cooling	8,629	11,942	14,250

Source: Author

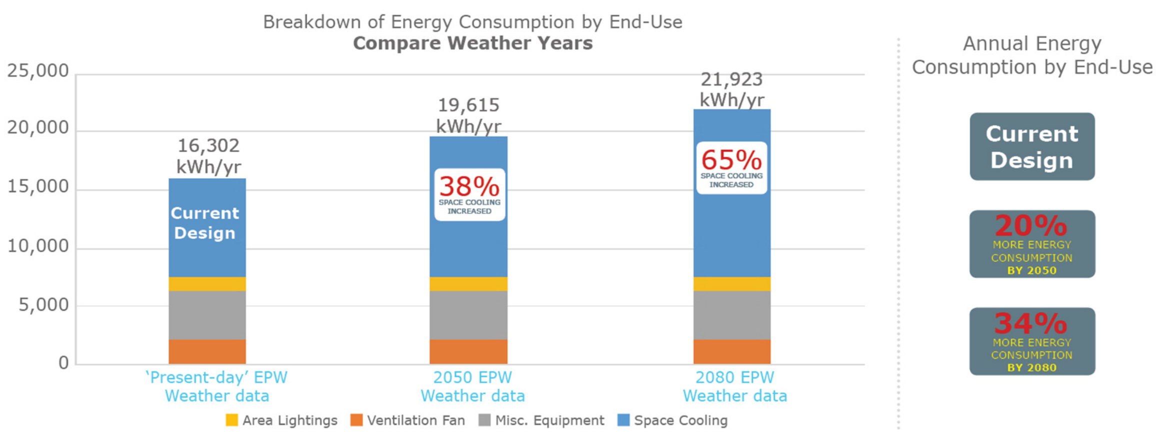


Figure 66. Annual energy consumption by end use and impact of future EPW weather data (2050 and 2080) for the Proposed Design model's energy use
Source: Author

Based on the simulation results for the present-day EPW weather data, the annual energy consumption by end use for the Proposed Design model was 16,302 kWh. In 2050, a 3,131 kWh (20%) increase was measured and in 2080, a 5,621 kWh (34%) increase was measured.

The breakdown of the model's annual energy consumption by end use and the results from the present-day EPW weather data show that the largest amount of energy use was from the annual space cooling in the HVAC system, which accounted for half of the total annual energy use (8,629 kWh), followed by miscellaneous equipment (4,176 kWh), ventilation fans (2,186 kWh), and area lighting (1,310 kWh). In 2050, the annual space cooling increased to 11,942 kWh, a 38% increase from the present-day time period. In 2080, the annual space cooling increased to 14,250 kWh, a 65% increase from the present-day time period.

10.4 Conclusion

The energy models created in eQuest focused on the building envelope design in order to assess the potential performance of the Frog building. The intent of this research is to quantify the Frog building's annual energy consumption and annual building heat gain, given its HVAC system, in relation to climate change. The simulated future weather data was used to analyze the characteristics of the three energy models. Each of these models was simulated separately, using each one's envelope specifications for walls, roof, and windows. The overall purpose of this study is to measure the effectiveness of using future weather data for designing a building envelope that will be energy-efficient now and in the future.

The study results support this project's hypotheses. The results for the simulation runs for each of the three energy models were anticipated due to prior knowledge of each model's different envelope designs as well as supporting research about the ways climate change can affect a building's energy consumption. Using the morphed EPW weather data, the simulation runs for each of the energy models showed increases in energy consumption. The morphed EPW weather data used in this study shows promise for aiding designers and engineers to better understand the conditions of the changing environment and the affects it will have on buildings.

PART 3:
EVALUATION AND CONCLUSION

Chapter 11: Analysis & Discussions

This chapter presents the analysis and discussion of the results laid out in chapter 10. This chapter first examines the role the sensitivity study plays in the envelope design in relation to the energy consumption of a building. This part of the chapter centers on a discussion of the performance of each model—Current Design, ASHRAE Design, and Proposed Design—in reference to the use of existing and future weather data from Meteonorm.

The Current Design model, the computer model of the Frog building developed in eQuest, was compared with the ASHRAE and Proposed Design models to evaluate whether the proposed building envelope improvements could perform better than the other two models and reduce the building's annual energy use and peak cooling load today and in the future. According to the simulation results, however, the Proposed Design model measured a 0.09% higher EUI and the ASHRAE Design model, a 13.04% higher EUI than that of the Current Design model in the present-day period (see table 25).

11.1 Analysis of Building Envelope for Energy Consumption

The amount of energy required for cooling a building depends on how well the envelope of that building is insulated. The thermal performance of a building envelope is determined by the thermal properties (ability to absorb or emit solar heat) of the materials used in addition to the overall U-value of the corresponding components: exterior wall, roof, window glazing, and SHGC. To determine whether energy can be saved by the proposed envelope design improvements under different climate conditions and how much, a proposed model was developed. This model proposed changes to the insulation values of the exterior wall, the roof, the window glazing, and the SHGC. For the simulations, the mechanical system of all three models was set to a constant variable (SEER 13), in order to better identify and understand the changes in building envelope across the models and whether each is able to reduce energy use. The occupancy schedule of the building, in all three models, was set to reflect the operational hours of a typical UHM building. The schedule follows the typical workweek, Monday through Friday, from 8:00AM to 6:00PM, and closed on the weekends. The list of holidays was set based on the standard US holiday schedule.

11.1.1 Energy Use Intensity (EUI)

To review, a building's EUI provides valuable energy performance metrics for the design energy modeling and assessment of building energy performance. The EUI is expressed as energy per square foot per year. It is calculated by dividing the total energy consumed by the building in one year (measured in kBtu) by the total gross floor area of the building. Generally, a low EUI signifies good energy performance.

Table 25. Annual building EUI comparison for Current Design, ASHRAE Design, and Proposed Design

	Present-Day (kBtu/sqft/yr)	2050 (kBtu/sqft/yr)	2080 (kBtu/sqft/yr)
Current Design	39.26	47.36	52.78
ASHRAE Design	44.38	52.47	58.06
Proposed Design	39.29	47.28	52.84

Source: Author

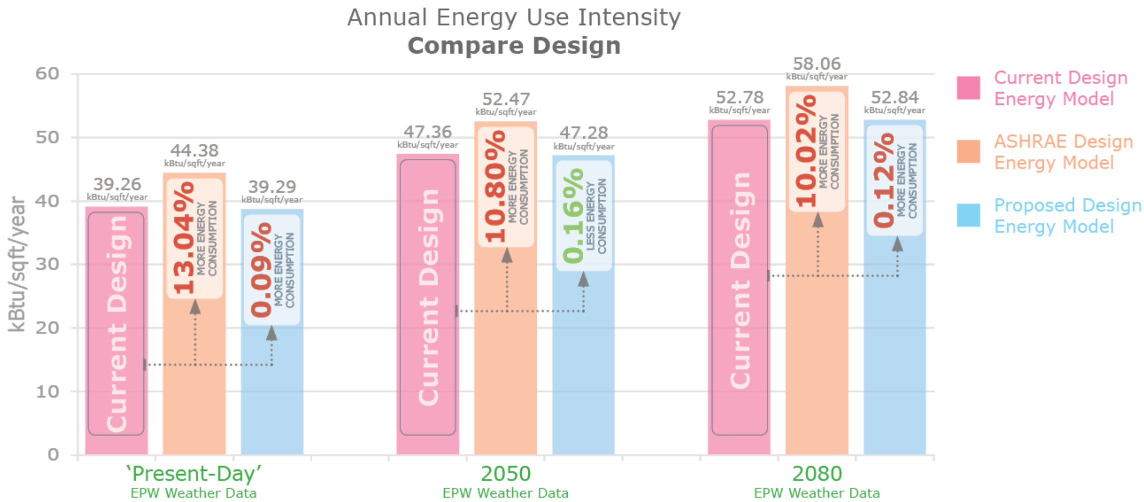


Figure 67. Annual building EUI comparison for Current Design, ASHRAE Design, and Proposed Design
Source: Author

Design Model Comparison

In all three models, energy use increased from present-day to 2050 and from 2050 to 2080 by about 20% and 30% respectively, see figure 68. This increase in energy consumption is due to increases in HVAC system load based on the predicted increase in average global temperature by 2 to 3°C by 2080 from present-day numbers. In addition, the building envelope design plays a major role in mitigating building energy use. A good envelope design will be more resilient to climate change impacts on building energy use.

Based on the simulation results from eQuest (see figure 67), the EUI for the Current Design model was 39.26 kBtu/sqft/yr for the present-day period. The ASHRAE Design model, in comparison, measured 44.38 kBtu/sqft/yr, or 13.04% more than the Current Design model, and the Proposed Design model, 39.29 kBtu/sqft/yr, or 0.09% more than the Current Design model. The Proposed Design model's higher energy use was unexpected. The hypothesis assumed that the Proposed Design model would use significantly less energy than the Current Design model due to added insulation. The results show, however, that the current envelope design seems to be optimized for the present-day time period and any additional insulation does not help to reduce energy use.

The results of the Frog building models' energy performance simulations using the 2050 future weather data show that the ASHRAE Design model used 10.80% more energy than the Current Design model. The Proposed Design model, however measured a reduction in energy use by 0.16%. The 0.16% reduction may appear insignificant but assuming energy costs increase in the future, this seemingly minor reduction could save on future energy costs.

The Frog building models' simulation results in the 2080 time period show that energy use continued to increase for all designs. The ASHRAE Design model used 10.02% more than the Current Design model, a 0.78% decrease in percentage difference from the 2050 measurements. The Proposed Design model used 0.09% more energy than the Current Design model, a 0.12% increase in percentage difference from the 2050 measurements. Surprisingly, the Proposed Design model ended up using more energy by 2080 than the Current Design model. This is possibly due to the high insulation values in the Proposed Design model. Further analysis of building end uses is needed to determine where the energy is being used.

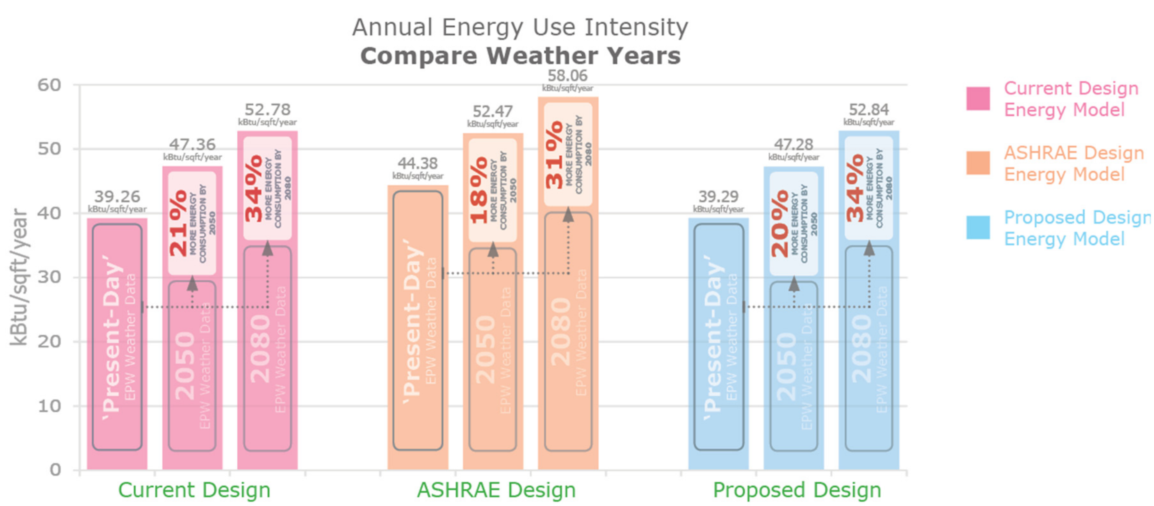


Figure 68. Annual EUI comparison for Present-day, 2050, and 2080
Source: Author

Weather Year Comparison

In 2050, the EUI for the Current Design model increased by 8.1 kBtu/sqft/yr (21%), jumping from 39.26 to 47.36 kBtu/sqft/yr. By 2080, the model's EUI measured 52.78 kBtu/sqft/yr, or 13.48 kBtu/sqft/yr (34%) higher than the present-day measurement. The ASHRAE Design model's EUI jumped from 44.38 to 52.47 kBtu/sqft/yr by 2050, an increase of 8.09 kBtu/sqft/yr (18%), and to 58.06 kBtu/sqft/yr by 2080, a 13.68 (31%) increase from the present-day measurement. Finally, the Proposed Design model's EUI increased by 7.99 (20%) in 2050, jumping from 39.26 to 47.28 kBtu/sqft/yr and by 2080, was 52.84 kBtu/sqft/yr, a 13.55 (34%) increase from the present-day measurement.

The results above show a surprising finding: the annual EUI for the Current and Proposed Design models increase significantly and similarly. By 2050, each model's measured EUI increased by about 20% and by 2080, by 34% from their present-day EUI measurements. The hypothesis assumed the Proposed Design model would also perform better in the future, but according to these results, it performed almost the same. This again might relate to the changes made to the insulation levels; the exterior wall insulation was changed from R-21 to R-35 and the roof from R-29 to R-65. It appears that the added insulation does not cause any considerable energy use savings. Again, further study needs to be conducted on building end uses to determine where the energy is being used.

11.1.2 Peak Cooling Load

To review, peak cooling load is used for sizing HVAC equipment in order to provide adequate heating or cooling under extreme weather conditions. In the case of the Frog building, due to Hawai‘i's hot and humid climate, the HVAC focus is on the cooling load. An undersized HVAC system will not be able to maintain the desired indoor temperature while an oversized one will be inefficient and struggle to maintain comfortable conditions, particularly with humidity control during summer months. Reducing the size of the cooling load can reduce the size of the mechanical system.

Table 26. Heat conduction and radiation of building envelope during peak cooling hours for Current Design (CD), ASHRAE Design (AD), and Proposed Design (PD)

	Present-Day (kBtu/h)			2050 (kBtu/h)			2080 (kBtu/h)		
	CD	AD	PD	CD	AD	PD	CD	AD	PD
Wall Conduction	1.011	2.632	0.506	1.116	3.061	0.602	1.208	3.551	0.762
Roof Conduction	0.477	1.203	0.157	0.519	1.382	0.219	0.566	1.604	0.269
Window Conduction	1.950	5.772	0.900	2.169	6.575	1.055	2.325	7.591	1.173
Window Radiation	0.113	0.043	0.056	**0.121**	0.047	0.061	**0.121**	0.043	0.070

Source: Author

Table 26 gives a breakdown of heat gain by conduction and radiation from wall, roof, and window glazing. In all models, the conduction and radiation for all envelope components increased at a steady pace from present-day period through to the 2080 period. However, the proposed envelope design showed the lowest overall heat gain. This is because of its higher insulation levels.

Window conduction was the largest contributor to heat gain in all design cases. Wall conduction was the second largest contributor to heat gain, followed by roof conduction, and finally window radiation. Window radiation for the Current Design model did not increase between 2050 and 2080 (see table 26). This could either reflect an error in the generated future weather data or indicate that the model's SHGC is optimized at 0.265 for the future conditions predicted under the A2 scenario.

Another important result occurs with the ASHRAE Design model's SHGC, which experienced a reduction between 2050 (0.047 kBtu/h) and 2080 (0.043 kBtu/h); the 2080 measurement was identical to the present-day measurement. Both the Current and ASHRAE Design models experienced either reduced or stable window radiation levels, whereas the Proposed Design model's steadily increased across the predicted periods, ending with an overall increase of 0.14 kBtu/h. The Current Design model's SHGC of

0.265 kBtu/h appears to be the ideal value for optimal performance across all three time periods.

Table 27. Peak cooling load for Current Design, ASHRAE Design, and Proposed Design

	Present-Day (Btu/h.sqft)	2050 (Btu/h.sqft)	2080 (Btu/h.sqft)
Current Design	32.29	33.69	35.78
ASHRAE Design	35.03	39.14	41.62
Proposed Design	29.73	31.07	34

Source: Author

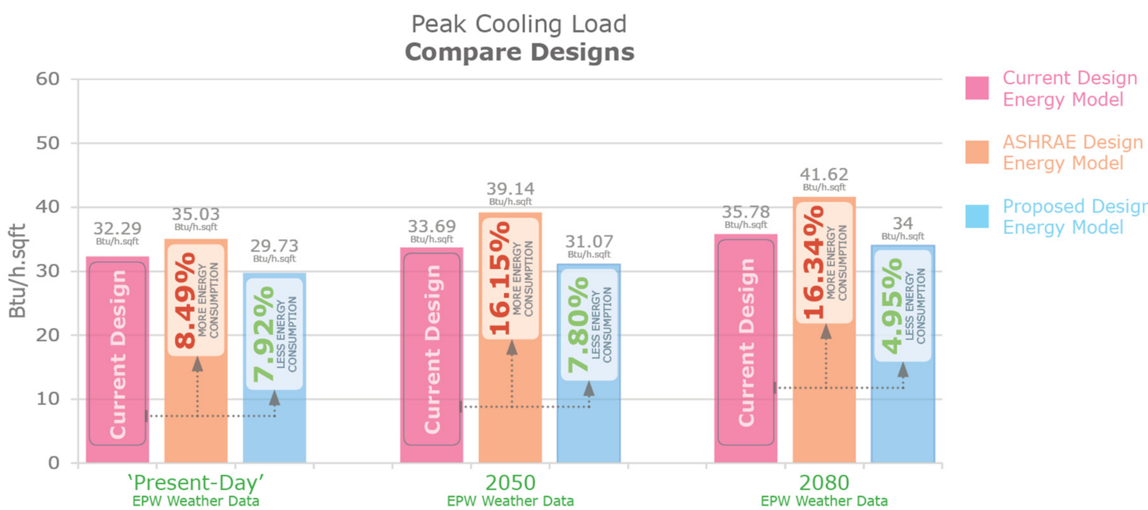


Figure 69. Peak cooling load for Current Design, ASHRAE Design, and Proposed Design
Source: Author

Design Model Comparison

The ASHRAE Design model's peak cooling load continued to increase through both 2050 and 2080, by about 19% overall. The peak cooling loads of the Current and Proposed Design models, on the other hand, both increased by 4% in 2050 and by 11% and 14%, respectively, in 2080 (see figure 70). This is partly due to the Proposed Design model's added insulation, which allowed the model to spend less energy for its peak cooling load. The envelope designs for the Current and ASHRAE Design models have lower insulation levels and therefore, in simulation, experienced increased peak cooling loads over time.

Based on the simulation results (see figure 69), the present-day peak cooling load for the Current Design model was 32.29 Btu/h.sqft. The ASHRAE Design model's present-day peak cooling load, in comparison, was 35.03 Btu/h.sqft, 8.49% higher than that of the Current Design model. The Proposed Design models' present-day peak cooling load, on the other hand, was 29.73 Btu/h.sqft, 7.92% lower than that of the Current Design model. In this aspect, the Proposed Design model performed better than the Current Design model with a peak cooling load reduction across all three time periods.

In 2050, the ASHRAE Design model's peak cooling load was 16.15% higher than that of the Current Design while the Proposed Design model's was 7.80% lower. This was again due to the insulation additions.

The peak cooling load of the ASHRAE Design model, like the Current Design model, continued to increase in 2080 and was measured at 41.62 Btu/h.sqft, 16.32% higher than the Current Design model's 2080 measurement. The Proposed Design model again measured a reduction in peak cooling load in 2080. However, the percent difference from the Current Design model's measurements (4.95%) was cut almost in half compared to the 2050 percent difference (7.80%). To analyze this further, table 26 shows the heat conduction and radiation of the building envelope during peak cooling hours. The window radiation for the Current Design model was measured at 0.121 kBtu/h.sqft for both 2050 and 2080. This model's window radiation neither increased nor decreased between these two periods whereas the Proposed Design model showed an increase in solar radiation from 2050 (0.061 kBtu/h.sqft) to 2080 (0.070 kBtu/h.sqft). This could mean that U-0.25 is the optimal window glazing U-value for the predicted climate conditions under the A2 scenario.

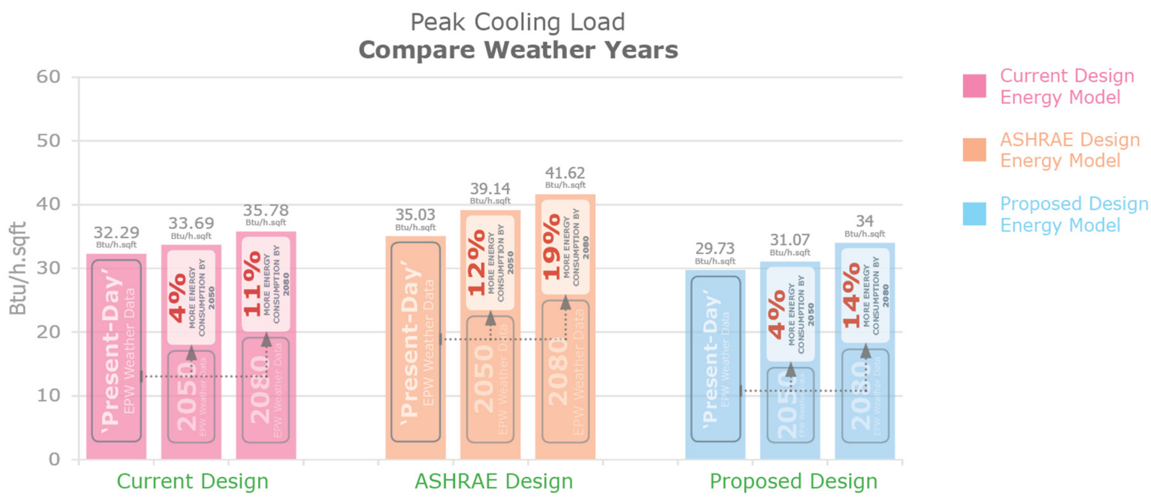


Figure 70. Peak cooling load comparison for Present-day, 2050, and 2080
Source: Author

Weather Year Comparison

Figure 70 displays the peak cooling load for all design models and weather periods. The peak cooling load for the Current Design in the present-day period was 32.29 Btu/h.sqft and increased by 4% or 1.4 Btu/h.sqft in 2050. In 2080, its peak cooling load increased by 11% or 3.49 Btu/h.sqft from 2050. The ASHRAE Design model's peak cooling load in the present-day period was 35.03 Btu/h.sqft and increasesd by 12% or 4.11 Btu/h.sqft in 2050. In 2080, its peak cooling load increased by 19% or 6.59 Btu/h.sqft from 2050. Finally, the Proposed Design model's peak cooling load, overall lower than the other models, in the present-day period was 29.73 Btu/h.sqft and increased by 4% or 1.34 Btu/h.sqft in 2050. In 2080, its peak cooling load increased by 14% or 4.27 Btu/h.sqft from 2050. When compared to the Current Design model peak cooling load results in each time period, the Proposed Design model's peak cooling load measured 7.92% less for the present-day period, 7.80% less for the 2050 period, and 4.95% less for the 2080 period. This reduction shows that the added insulation successfully kept the outside temperature out.

In relation to peak cooling load, the proposed envelope design changes to the Frog building's insulation levels positively affected the building's performance in all three time periods, measuring an overall reduction in cooling load over time, compared to the other two models who both measured overall increases in cooling loads over time. To put it another way, the added insulation to the wall and roof allowed the Proposed Design model to be more resilient to heat gains because less conduction and radiation passed through the building envelope. Even with these peak cooling load results, however, the Proposed Design model's annual EUI measurements increased in both 2050 and 2080, in a similar pattern to that of the Current Design model (see figure 67). In this case, the significant reduction in peak cooling load did not help reduce overall annual EUI. In the following section, building end uses will be analyzed to identify which elements of the end use are using the energy.

11.1.3 End Use

This section analyzes the annual breakdown of energy consumption by end use for each of the design models under the A2 emissions scenario for the present-day, 2050, and 2080 time periods. Due to time limitations, this research focused on the following four end uses:

1. Space cooling: Energy used to remove indoor heat, required for indoor thermal comfort
2. Area lighting: Overhead lighting
3. Miscellaneous equipment: Plug loads
4. Ventilation fan: Supply, return, and exhaust fans

Table 28. Annual energy use by end use comparison for Current Design, ASHRAE Design, and Proposed Design

	Present-Day (kWh/yr)	2050 (kWh/yr)	2080 (kWh/yr)
Current Design	16,287	19,647	21,896
ASHRAE Design	18,412	21,769	24,091
Proposed Design	16,302	19,615	21,923

Source: Author

Table 29. Annual energy use breakdown by end use for Current Design, ASHRAE Design, and Proposed Design

	Breakdown by End Use	Present-Day (kWh/yr)		2050 (kWh/yr)		2080 (kWh/yr)	
Current Design	Space Cooling	**8,615**	**(53%)**	**11,975**	**(61%)**	**14,224**	**(65%)**
	Area Lighting	1,310	(08%)	1,310	(07%)	1,310	(06%)
	Misc. Equipment	4,176	(26%)	4,176	(21%)	4,176	(19%)
	Ventilation Fan	2,186	(21%)	2,186	(11%)	2,186	(10%)
ASHRAE Design	Space Cooling	**8,879**	**(48%)**	**12,237**	**(56%)**	**14,559**	**(61%)**
	Area Lighting	3,170	(17%)	3,170	(15%)	3,170	(13%)
	Misc. Equipment	4,176	(23%)	4,176	(19%)	4,176	(17%)
	Ventilation Fan	2,186	(12%)	2,186	(10%)	2,186	(09%)
Proposed Design	Space Cooling	**8,629**	**(53%)**	**11,942**	**(61%)**	**14,250**	**(65%)**
	Area Lighting	1,310	(08%)	1,310	(07%)	1,310	(06%)
	Misc. Equipment	4,176	(26%)	4,176	(21%)	4,176	(19%)
	Ventilation Fan	2,186	(13%)	2,186	(11%)	2,186	(10%)

Source: Author

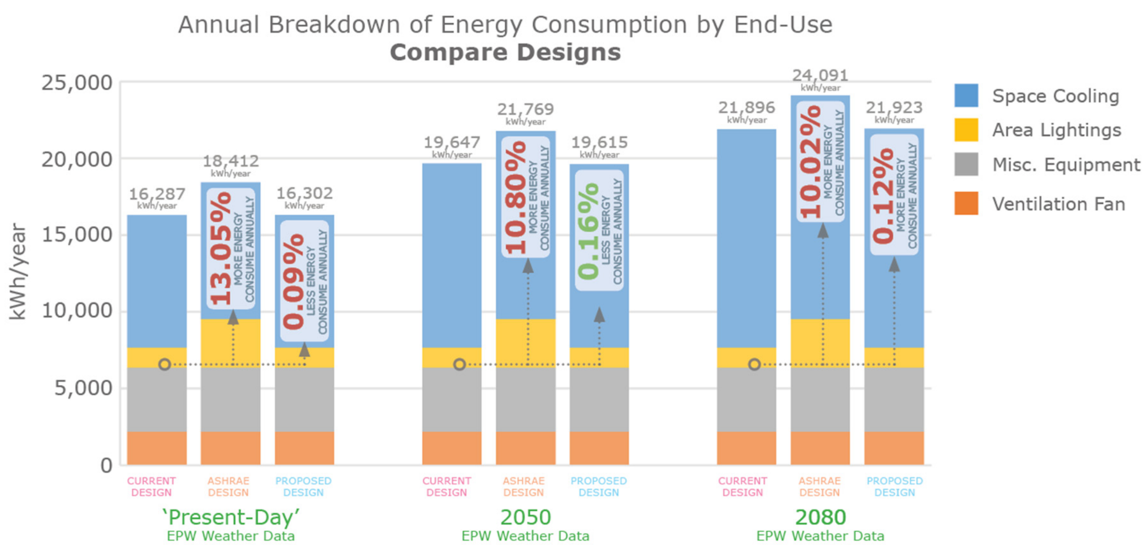


Figure 71. Annual energy use by end use comparison for Current Design, ASHRAE Design, and Proposed Design
Source: Author

Figure 71 displays the annual energy use by end use for each design model in each time period. In the present time-period, the Current Design model consumed a total of 16,287 kWh/yr, the ASHRAE Design, 18,412 kWh/yr, and the Proposed Design 16,302 kWh/yr. As stated in the EUI discussion, the Proposed Design model used 0.09% more energy than the Current Design model in the present-day period, 0.16% less in the 2050 period, and again 0.12% more in the 2080 period. The Proposed Design model has higher insulation values and yet it did not perform better than the Current Design model in the present-day period or in the 2080 period. The reason for this energy use trend likely relates to the building envelope design. Further analysis of building end use will be conducted in the following section.

Table 29 shows that energy consumed for space cooling was 53% of the Current Design model's overall energy use, 48% of the ASHRAE Design model's overall energy use, and 53% of the Proposed Design model's overall energy use. Space cooling used by far the greatest percentage of annual energy in all three models and therefore, the end-use analysis will focus on space cooling.

Space Cooling

Table 30. Annual energy consumption for space cooling comparison for Current Design, ASHRAE Design, and Proposed Design

	Present-Day (kWh/yr)	2050 (kWh/yr)	2080 (kWh/yr)
Current Design	8,615	11,975	14,224
ASHRAE Design	8,879	12,237	14,559
Proposed Design	8,629	11,942	14,250

Source: Author

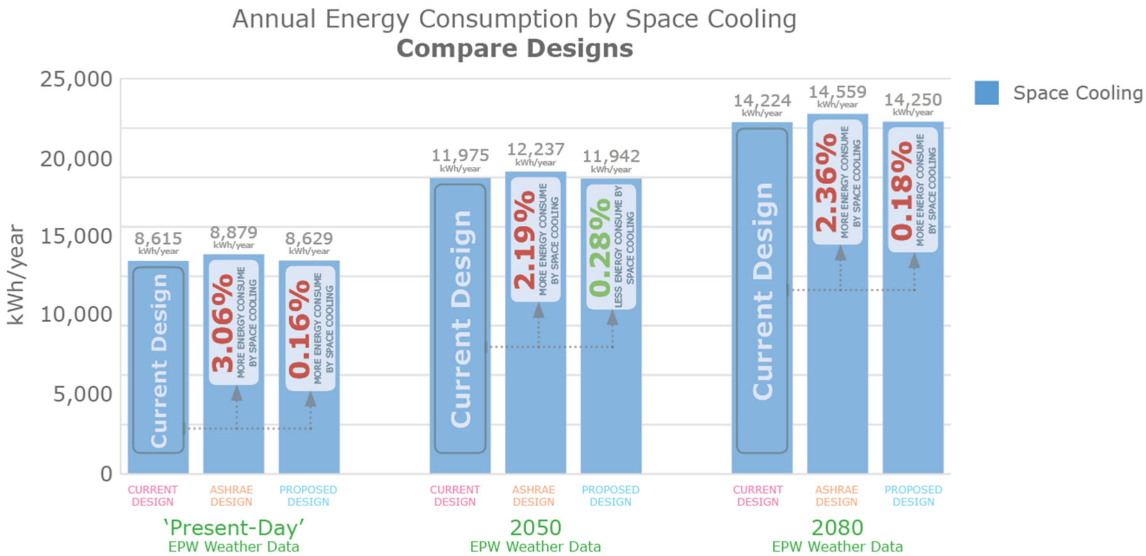


Figure 72. Annual energy consumption for space cooling comparison for Current Design, ASHRAE Design, and Proposed Design
Source: Author

The cooling load of a building is affected by both external and internal sources. A building absorbs external heat from solar radiation, conductive heat gain, and infiltration of hot air. Internal heat can be generated from its occupants, lights, computers and other electrical equipment. Thus, space cooling is the energy used to cool a building to maintain a comfortable and productive indoor environment. Due to the scope of this study, I will only focus on heat flow from the building envelope.

Figure 72 presents a breakdown of space cooling demand for all three models in all three time periods. In the present-day period, the space cooling demand for the Current Design model was 8,615 kWh/yr. In the same period, the ASHRAE Design model's space cooling demand was 8,879 kWh/yr, 3.06% higher than that of the Current Design, and the Proposed Design model's space cooling demand was 8,629 kWh/yr, 0.16% higher than that of the Current Design.

In 2050, the ASHRAE Design model used 2.19% more cooling energy than the Current Design model while the Proposed Design model used 0.28% less. In 2080, the HVAC system's space cooling demand continued to increase in all three models, but especially in the ASHRAE Design model. This model's space cooling demand was

14,559 kWh/yr, or 2.36% higher than that of the Current Design model. The Proposed Design model's space cooling demand was 14,250 kWh/yr, or 0.18% higher than that of the Current Design model.

The Proposed Design model's higher percentage in both the present-day and 2080 time periods than that of the Current Design model appears to be from window radiation level differences. Table 26 shows the Current Design model's window radiation was 0.121 kBtu/h.sqft in both the 2050 and 2080 time periods. There was no measured increase between the two periods. For the Proposed Design model, however, a 0.070 kBtu/h.sqft increase in window radiation was measured between 2050 and 2080. As a result, the space cooling for the Current Design model measured significantly lower than that of the other two designs. These results could represent a mistake in the EPW weather data or, as stated before, this could signify that U-0.25 is the optimal window glazing U-value for the predicted climate conditions under the A2 scenario.

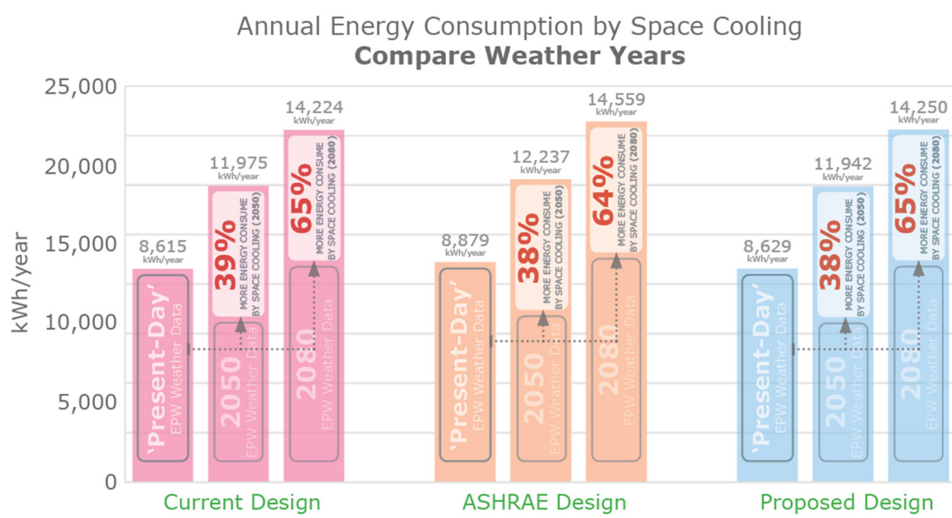


Figure 73. Annual energy consumption for space cooling comparison for Present-day, 2050, and 2080
Source: Author

Weather Year Comparison

Figure 73 shows each model's annual space cooling energy use change from the present-day to the 2050 period and from the present-day to the 2080 period. On average, the three models experienced a 38% increase in 2050 from present-day results and a 65% increase in 2080 from present-day results. This is likely due to both the 2 to 3°C predicted increase in average global temperatures by 2080 as well as the building envelope design that caused building heat gain and led to increases in energy use for space cooling.

Based on the sensitivity study results detailed in chapter 9, the Proposed Design model was expected to use 2% less annual energy than the Current Design model in the present-day time period. In addition to this, according to simulation results, the Proposed Design model's peak cooling load was 7% less than that of the Current Design model in the present-day period. The hypothesis assumed that the proposed improved envelope would reduce daytime external heat gain and thus reduce the energy needed for the removal of heat from within. It is possible, however, that the proposed improved envelope might be trapping heat indoors, causing the space cooling demand to increase. Alternatively, the results may be showing that the current envelope design is already optimized for our current climate as well as those predicted for the future according to the A2 predicted emissions scenario. What can be concluded here is that adding any more insulation would not result in decreases in energy use for the Frog building.

11.2 Annual hourly cooling load analysis for Current and Proposed Design Models

In this study, space cooling was the largest building end use for all three models. Even though the hypothesis assumed the Proposed Design model would perform better, both the Current and Proposed Design models measured similar increases in annual space cooling energy use. As reported, during the present-day period, the Proposed Design model's peak cooling load measurement was 7.92% less than that of the Current Design model, which led me to hypothesize that the Proposed Design model would also use less energy over the course of the year. However, the results showed this to be false; the Proposed Design model used 0.16% more energy in annual space cooling than the

Current Design model in the present-day period. The hypothesis presupposed that the Proposed Design model would use less energy for space cooling than the current envelope design due to the changes proposed to its envelope design. Higher insulation levels did lead to a reduction in daytime external heat gain, which in turn, reduced the peak cooling load energy use, but not the annual space cooling use.

The next step is to discuss possible reasons the two models resulted in similar annual energy use measurements but different peak cooling load measurements. Further, more in-depth analysis needs to be conducted on the annual hourly cooling load data from the simulation results. The cooling load is the hourly rate at which heat must be removed from a building in order to maintain the desired indoor thermal comfort level. Therefore, taking a second, closer look at the annual hourly cooling load might clarify the simulation results for the Proposed and Current Design model comparison.

11.2.1 Histogram for cooling loads study

Table 31. Annual cooling energy use and peak cooling load for the Current Design and Proposed Design

	Present-Day		2050		2080	
	CD	PD	CD	PD	CD	PD
Energy (kBtu/year)	148,082	**148,982**	205,241	**205,856**	242,594	**246,762**
Peak Cooling Load (kBtu/h)	**196**	194	216	**217**	**234**	233

Source: Author

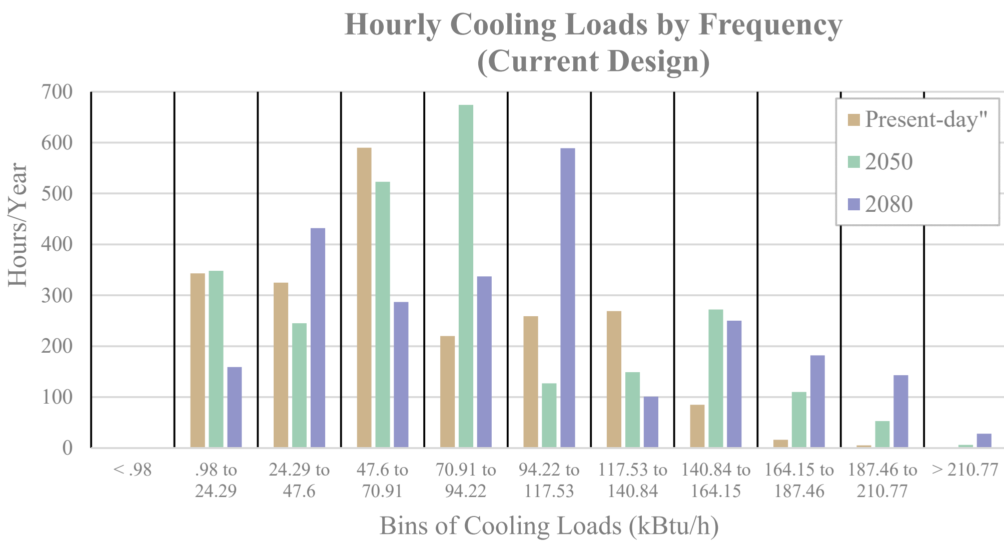


Figure 74. Histogram with hourly cooling loads frequency for Current Design
Source: Author

Table 32. Number of hours/year of occurrences for the bin ranges for Current Design

	Bins of Cooling Loads (kBtu/h)										
	<.98	.98 to 24.29	24.29 to 47.6	47.6 to 70.91	70.91 to 94.22	94.22 to 117.53	117.53 to 140.84	140.84 to 164.15	164.15 to 187.46	187.46 to 210.77	>210.77
Present-day hours per year	0	343	325	590	220	259	269	85	16	5	0
2050 hours per year	1	348	245	523	674	127	149	272	110	53	6
2080 hours per year	0	159	432	287	337	589	101	250	182	143	28

Source: Author

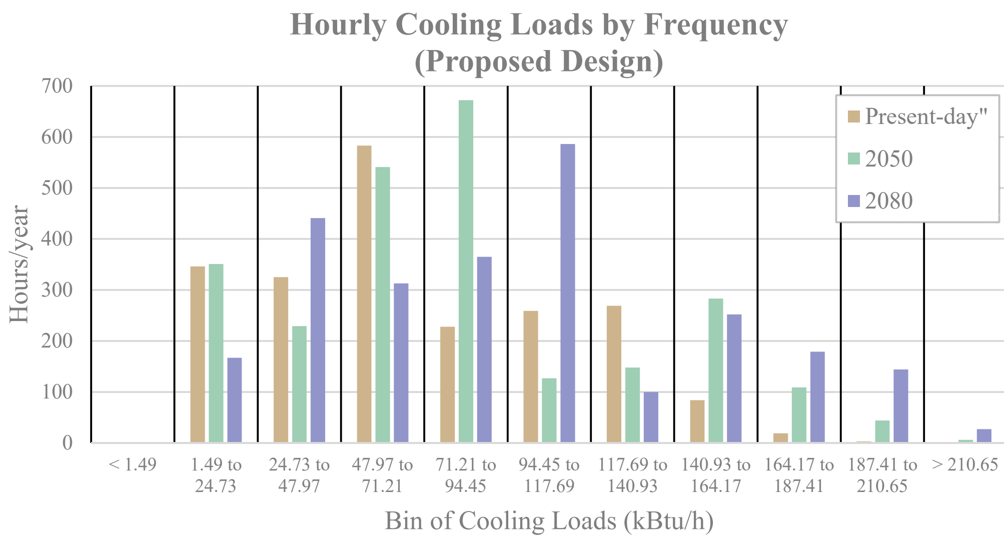


Figure 75. Histograms with hourly cooling loads frequency for Proposed Design
Source: Author

Table 33. Number of hours/year of occurrences for the bin ranges for Proposed Design

	Bins of Cooling Loads (kBtu/h)										
	<1.49	1.49 to 24.73	24.73 to 47.97	47.97 to 71.21	71.21 to 94.45	94.45 to 117.69	117.69 to 140.93	140.93 to 164.17	164.17 to 187.41	187.41 to 210.65	>210.65
Present-day hours per year	0	346	325	583	228	259	269	84	19	3	0
2050 hours per year	0	351	229	541	672	127	148	283	109	44	6
2080 hours per year	1	167	441	313	365	586	100	252	179	144	27

Source: Author

Table 34. Total cooling hours/year and annual peak cooling load use for Current and Proposed Designs

	Present-Day		2050		2080	
	CD	PD	CD	PD	CD	PD
Hourly Counts	2,112	**2,116**	2,508	**2,510**	2,508	**2,575**
Annual Cooling Load (kBtu/h/year)	146,459	**147,924**	204,156	**204,915**	246,160	**246,499**

Source: Author

According to the online *American Heritage Dictionary of the English Language*, a histogram is "[a] bar graph of a frequency distribution in which the widths of the bars are proportional to the classes into which the variable has been divided and the heights of the bars are proportional to the class frequencies." In this case, the annual hourly space cooling data acquired from the eQuest output were input into an Excel histogram. The annual hourly cooling load data was divided between a range of bins set along the x-axis where each bin represents a certain range of cooling load values (see figure 74 and figure 75). The graph's y-axis represents number of hours per year. It is important to note that the low and high values along the x-axis, 0.98 kBtu/h and 210.77 kBtu/h, as shown in figure 74, represent the Current Design model's minimum and maximum cooling load values from all three time periods.

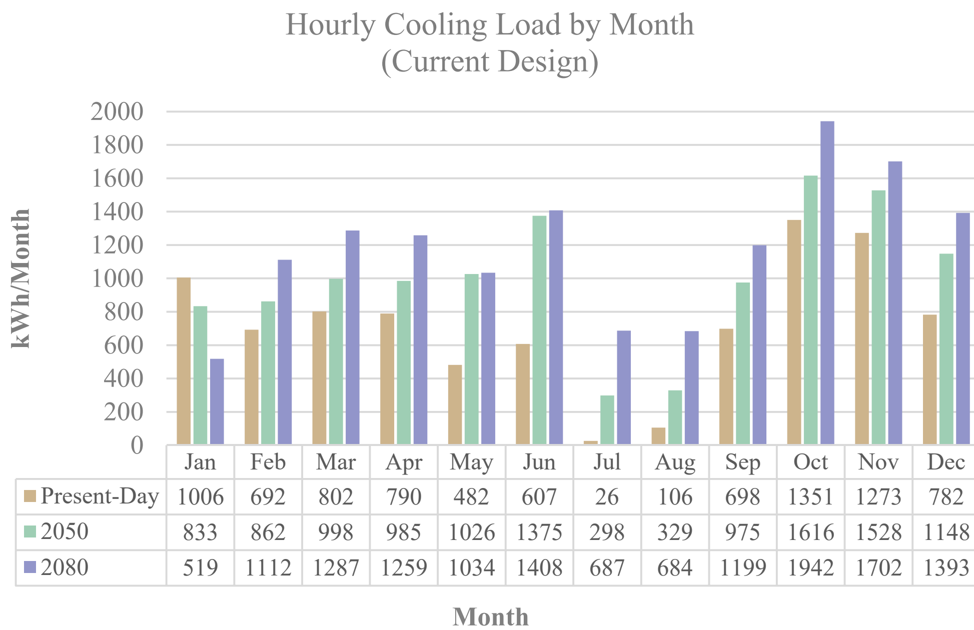
Based on the two histograms above, the cooling load of both the Current and Proposed Design models continuously increased from the present-day time period through the 2080 period. Looking at the present-day results, most cooling load values fall in the lower end of the bin range compared to those of the 2050 period, which are mostly represented in the middle range, and those of the 2080 period, which are mostly represented in the higher range.

Furthermore, the results also suggest that the Proposed Design model's higher energy use, even though it resulted in a smaller peak cooling load than the Current Design, is due to the greater number of hourly cooling load counts than those of the Current Design model for all three time periods (see table 34). As shown in table 31, the annual energy use for the Proposed Design model is 1 to 2% higher than that of the Current Design model for all time periods. The annual energy use from the histogram was derived using the following formula:

Hours/Year (h/yr) x Average Bin of cooling load (kBtu/h) = Energy (kBtu/yr)

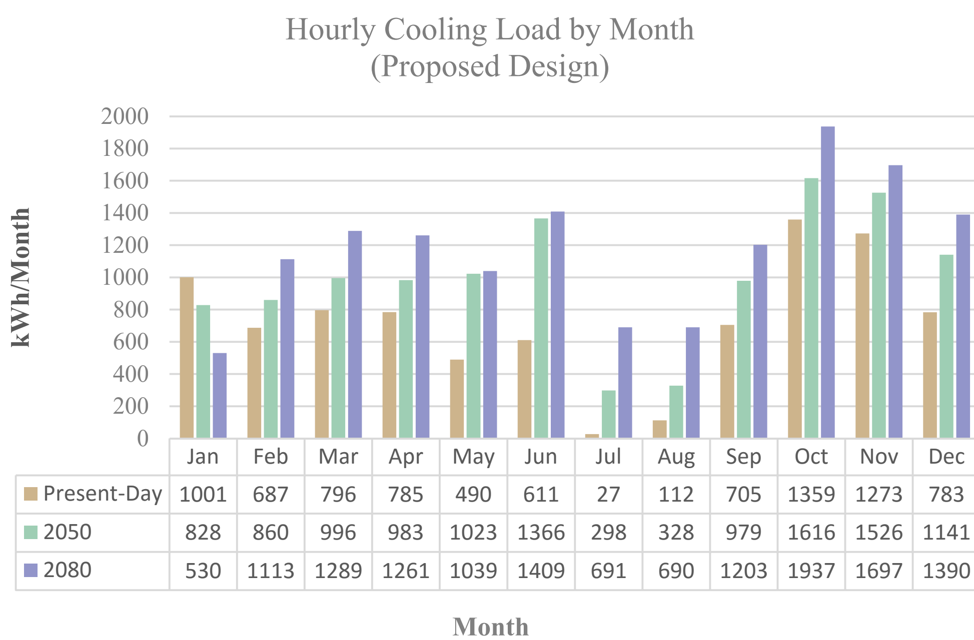
To conclude, this analysis shows that the comparison of the present-day weather data to that of 2050 and 2080 using a histogram is helpful in analyzing how climate change can impact the cooling load and energy use of the building in all three time periods. The results for the histograms of both the Current and Proposed Design models show a gradual increase in cooling load demand from the present-day, to 2050, to 2080 time periods. In addition, the study was able to explain why the Proposed Design model used more annual energy even though it had lower peak cooling loads than the Current Design in all three time periods. Based on the histogram, the Proposed Design had a higher number of hour counts than the Current Design, which led to more energy use. See appendix F for a comparison of hourly cooling load between winter and summer months.

11.2.2 Hourly cooling energy by month



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Present-Day	1006	692	802	790	482	607	26	106	698	1351	1273	782
2050	833	862	998	985	1026	1375	298	329	975	1616	1528	1148
2080	519	1112	1287	1259	1034	1408	687	684	1199	1942	1702	1393

Figure 76. Comparison of hourly cooling load by month for Current Design for Present-day, 2050, and 2080
Source: Author



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Present-Day	1001	687	796	785	490	611	27	112	705	1359	1273	783
2050	828	860	996	983	1023	1366	298	328	979	1616	1526	1141
2080	530	1113	1289	1261	1039	1409	691	690	1203	1937	1697	1390

Figure 77. Comparison of hourly cooling load by month for Proposed Design for Present-day, 2050, and 2080
Source: Author

Figure 76 and figure 77 above show the hourly cooling energy use by month of the Current and Proposed Design models. First, I would like to point out an error I found during this part of the research regarding the weather data. The cooling energy use for January might be an error from the weather files generated with the Meteonorm software. According to the weather data generated with Meteonorm, the global temperature in the month of January in each time period was much higher than the weather data reports from the US Department of Energy (DOE). However, the Meteonorm data for the other months is similar to the DOE data. Therefore, the data from January has been excluded from the following analysis and discussion.

The figures above show a significant trend: for every month except January in both models, the results continuously increase from the present-day time period to that of 2050 to that of 2080. Both models used a similar amount of cooling energy each month. The parallel decrease in energy use during the months of July and August is interesting to note, as is the large increase in energy use from September to October. These results, however, can be easily explained by the building occupancy schedule.

The building occupancy schedule is set up to reflect the operational hours of a typical UHM building. The schedule reflects the typical workweek, from Monday to Friday, from 8:00AM to 6:00PM, and closed on the weekends. The list of holidays was set based on the standard US holiday schedule (see table 35).

Table 35. Building occupancy schedule

Ending Month	Ending Day	Week Schedule	Description:
January	6	Low Energy Use	Winter Break
March	22	High Energy Use	Spring Semester
April	7	High Energy Use	Spring Semester
June	14	High Energy Use	Spring Semester/ Summer break
July	14	Low Energy Use	Summer Break
September	20	Low Energy Use	Summer Break
October	6	High Energy Use	Fall Semester
December	13	High Energy Use	Fall Semester
December	31	Low Energy Use	Winter Break

Source: Author

Additionally, the building end use loads, including area lighting, miscellaneous equipment, ventilation fan, equipment, and space cooling are set up to follow the building occupancy schedule. Assuming these end uses follow the occupancy schedule, during school sessions they will be considered high energy users and vice versa, during winter and summer break, it will considered to be low energy use. The only exception is the ventilation fan, which is set up to turn off after hours and during school breaks. Therefore, the reason less cooling energy was measured for July and August is because of less energy was used during the summer break, as shown in table 35.

The large increase in cooling energy use for the month of October is likely because this is the start of the fall semester and the building is being occupied again after having been on standby mode during the summer break months of July and August. The equipment and system switch from standby to operation mode usually, at first, uses a great amount of energy before it steadily decreases in the cooler winter months, November and December, which can be seen in both model’s results.

11.3 Conclusion

This chapter discussed and analyzed the simulation results of the Current and Proposed Design models using EUI, peak cooling load, and space cooling (end use) as metrics for the final results comparison.

In all three models, the EUI increased from the present-day to the 2050 period by about 20% and from the 2050 to the 2080 period by about 30%. This is due to the increases in energy use demand for space cooling resulting from the predicted increase in average global temperatures by 2 to 3°C by 2080. However, both the Current and Proposed Design models experienced similar results in energy use in all three time periods. A possible reason for this might be that the Proposed Design model's added insulation acted counterproductively. As previously stated, the added insulation may offer no considerable energy savings to the envelope design.

A second finding that was significant was that the Proposed Design model's peak cooling loads were between 4.92% and 7.92% lower than those of the Current Design model in all three time periods (see Figure 69). The Proposed Design model's added insulation, in this case, was able to reduce the peak cooling load. However, whereas the Proposed Design model's peak cooling load in 2050 was 7.80% less than that of the Current Design model, in 2080, it was only 4.95% less. In order to understand this difference and to ascertain where the heats gains were coming from, heat conduction and radiation through each model's building envelope during peak cooling hours was studied. For both the 2050 and 2080 time periods for all models, window conduction and radiation was the largest contributor to heat gains. The Current Design model's results stood out the most because the radiation gain didn't change between 2050 and 2080; the radiation level remained the same, at 0.121 kBut/h, for time periods. It may be that the Current Design model's SHGC (0.265) and window glazing U-value (U-0.25) are optimized for the A2 scenario predicted climate conditions in 2050 and 2080.

The two findings discussed above seem to contradict each other. The Current and Proposed Design models obtained similar EUI results. However, the Proposed Design model's peak cooling load in each time period was smaller than that of the Current Design model. Further building end use analysis was conducted to bring light to the situation. Because space cooling load, in all models and all time periods, used by far the most energy of all the building end uses, space cooling load alone was analyzed. In all three models, in 2050, the annual space cooling energy results increased from the present-day results by an average 38% and in 2080, by an average 65%.

Based on the sensitivity study results, the hypothesis assumed that the Proposed Design model, in the present-day time period, would experience a 2% reduction in annual energy use. In addition, some EUI savings should have been obtained from the Proposed Design model's 7.92% reduction in peak cooling load in the same period. The hypothesis assumed that the proposed envelope design would reduce energy use by reducing daytime external heat gain, which in turn would reduce the energy needed for the removal of heat. To speculate, it might be that the proposed envelope design is absorbing heat during the day and radiating it indoors at night.

Based on the space cooling (end use) analysis, the Proposed Design model used more energy for space cooling than anticipated. Even though, compared to the Current Design model, the Proposed Design model experienced a lower peak cooling load, it also experienced a higher frequency of hour counts for space cooling. The higher number of hour counts, in this case, resulted in the model's greater energy demand for the removal of heat from the building.

Chapter 12: Conclusion & Strategies

Summary of study objective

The main objective of this research was to explore the value of properly accounting for climate change during the building design process. This was achieved in part by applying predicted future weather files to building energy simulations of three building envelope models of one of the HNEI Frog buildings currently under construction at the UHM to discover whether improvements can be made now to the building envelope that can reduce the energy use and peak cooling loads of the building in the future.

The methodology for this research can be divided into three parts. First, future weather files were created using a future EPW weather data generator for use in the simulations. Hourly future weather data was produced based on the IPCC A2 (second highest emissions) projected climate scenario in tropical regions for the present-day, 2050, and 2080 periods. Second, a sensitivity study was implemented to determine the building envelope specifications for the Proposed Design model. The study examined four energy-affecting variables including: the exterior wall R-value, the roof R-value, the window glazing U-value, and solar heat gain coefficient (SHGC) value. The Frog building's original design was used as the case study subject. Finally, building energy simulations using the future EPW weather data were conducted to evaluate the three models' building envelope energy use responses to future climate predictions. The goal was to determine whether the Proposed Design model's building envelope would perform better over the three time periods than the Frog building's current design model and the ASHRAE Standard design model.

Summary of methodology

The use of present-day weather files to create simulated future weather data is an area of development in the field of building design that has more recently gained attention. Research thus far has established that future climate condition predictions are the starting point for evaluating the impacts of climate change on building envelope performance. This project focused on the assessment of building envelope performance and annual energy use under the A2 projected climate scenario, and used the metrics energy use intensity (EUI), peak cooling load, and energy consumption by end use, as forms of measurement for the final comparison of the research results.

In order to set up a realistic energy model, it was necessary to find and gather relevant information on the building geometry and construction details. The Frog building was modeled in eQuest using information gathered from its architectural drawings and manufacturer data provided by the HNEI and UHM. A detailed energy model was thus set up representing the whole building. To investigate a wide range of envelope design options, three energy models were created, each with different envelope assemblies but with the same mechanical system inputs. These models are: the Current Design model, the exact Frog building specifications of the HNEI university classroom building; 2) the ASHRAE Standard 90.1-2010 Design model, the Frog building specifications with changes according to the ASHRAE Standard; and 3) the Proposed Design model, the Frog building specifications with changes based on the sensitivity study results. These energy models were then input into BES software using the present-day and future (2050 and 2080) Honolulu International Airport weather data prepared with Meteonorm.

Summary of results

This study focused on the measurable predicted impacts of future weather on a building's energy use and building envelope design. The Proposed Design model was compared with the Current Design model to determine which of the two models would consume the least annual energy during each of the three time periods. The Proposed Design model was drawn up based on the results of the sensitivity study that identified the most energy-efficient values of four variables, which together provided an overall assumed annual energy savings of about 2% for the present-day time period (exterior wall R-value showed a 0.14% annual energy savings; roof R-value, 0.19%; window glazing U-value, 0.08%; and SHGC, 1.58%).

With the future EPW weather data, it was possible to evaluate future building energy use and thermal performance under the influences of climate change for each of the three models. According to the simulation results, all three models showed substantial increases in annual energy use during each of the future time periods. The Current Design used 21% more energy in 2050 and 34% more in 2080; the ASHRAE Design used 18% more energy in 2050 and 31% more in 2080; and the Proposed Design used 20% more energy in 2050 and 34% more in 2080. The significant increases in percentage of annual energy use for all three models in both predicted future time periods is likely due to the rise in global temperatures that will increase heat gain within buildings, which in turn will lead to increases in the amount of cooling energy required for indoor thermal comfort.

According to the simulation results, the Proposed Design model used 0.09% more energy than the Current Design for the present-day time period and 0.12% more for the 2080 time period. In 2050, however, the Proposed Design used 0.16% less energy. These percentages show that the Proposed Design model's higher insulation levels (R-35 for wall and R-65 for roof) were largely counterproductive even though it was hypothesized that the higher levels would help reduce the energy use across all three periods. It is possible that the higher insulation levels cause the building to trap heat at night whereas the current building, with its lower insulation values, is better able to release heat. The trapped heat and radiation caused by direct and diffuse solar radiation transmitted during the day from the insulation and window conduction caused the HVAC system to use more energy to cool the building and adjust for thermal comfort. The results show that over-insulating a building might not be beneficial for hot and humid climate zones due to heat trapping and heat radiating indoors at night.

Recommendation

Based on the results of this research, of the three Frog building models, the Current Design model represents the optimal design. There is no need to increase insulation in any part of the building envelope. However, if the building does require more insulation, then I would recommend choosing only one component to improve—either the wall or the roof insulation. Alternatively, I would recommend focusing on improving the SHGC first because, of the four measured variables, it was the variable that made the most notable reduction (1.58%) in annual energy use. Secondly, improving the window glazing material to include double-glazing or low-E glass with warm edge-sealing techniques, and better edge-sealing techniques. The materials and design for the window frame also influence thermal performance. Low conductive materials, such as vinyl and composite materials, perform better than high conductive materials such as aluminum.

The following recommendations are not based on the present study but should be considered for passive design strategies. The present study shows that window conduction and radiation are among the largest contributors to heat gain in a building. Providing more outdoor shading, such as trees next to the building, can help reduce solar radiation and lower surrounding temperatures through evapotranspiration. Implementing natural ventilation strategies for the building can also help cool the interior space and reduce energy consumption. Smart systems that control the energy use of lighting, like daylight and occupancy sensors, can also help reduce the building's overall energy use.

Recommendation for future research

Climate change significantly impacts the energy use and thermal performance of buildings. This research focused on using future weather data in building energy simulations to help the designer assess the future impacts of climate change on building energy and thermal performance, a process that allows the designer to question his or her own speculations and assumptions about the design. Additionally, the research on future weather data development conducted in this work can be applied to other future periods and greenhouse gas emissions scenarios.

Further study is recommended to investigate the impacts of the other IPCC future weather data scenarios on building energy use across a range of time periods; these studies should focus on the energy and thermal performance of a building's design features including thermal mass, window-to-wall ratio, overhang shading, green roof system, natural ventilation strategy, and more.

Conclusion

As previously stated, the main goal of this research project was to consider the future impacts of the earth's changing climate on the annual energy use of a building. This was accomplished by conducting a series of simulations on three models of the HNEI Frog building using future EPW weather data for three time periods under the IPCC A2 projected climate scenario. The hypothesis supposed that proposed improved building insulation level, window glazing value, and SHGC would decrease the annual energy use and cooling load of the building. It also supposed that the proposed improved envelope design would perform better in each of the three time periods—present-day, 2050, and 2080. It also sought to discover whether changing the exterior wall R-value, (from R-21 to R-35), roof R-value (from R-29 to R-65), window glazing U-value (from U-0.25 to U-0.15), and SHGC (from 0.265 to 0.15) would decrease the annual energy use and cooling load of the building.

The results, however, did not support the hypothesis. The proposed improvements to the building envelope design did not reduce the annual energy consumption and cooling load of the building. It is possible that over-insulation of a building envelope can be counterproductive in tropical climate zones because the added insulation could be both causing the building to trap heat at night and less able to radiate this heat to the outside at night, leading to an increase in cooling energy requirements for indoor thermal comfort.

The under-insulation of a building envelope, however, can also cause increases in annual energy use due to heat gain as was seen in the ASHRAE Design model results.

Based on the sensitivity study, the annual energy savings from the wall insulation seems to be less significant than the annual energy savings from the SHGC (a measure of how well window glazing blocks heat cause by solar radiation). The proposed wall and roof insulation changes resulted in a combined annual energy savings of 0.33% compared to the SHGC, with a 1.58% annual energy savings. Changing the building envelope insulation from R-21 to R-35 (wall) and R-29 to R-65 (roof) made a small difference in annual energy savings whereas changing the SHGC from 0.265 to 0.15 made a notable differences in annual energy savings. Therefore, for the future, I recommend a greater focus be placed on improving the SHGC rating.

The design model simulation results for each weather year were useful for understanding the energy performance of each model over time, against itself and compared to the others. For all design models, the results showed similar trends of progressive increase across the three time periods for EUI, peak cooling load, and space cooling (end use). These increases were likely caused by 2 to 3°C predicted increase in average global temperatures by 2080.

This study allowed for a better understanding of the envelope design and building energy use for both present-day and predicted future time periods. By using the most current building energy simulation technology and future weather data, this analysis approach can help designers to estimate the overall performance of the whole building over a long period of time and thus design a more efficient building envelope.

To conclude, I understand that future weather data is not commonly used today; it is still a new concept, a different way of looking at building performance. In my opinion, using future weather data, such as the data developed for this study, for building energy simulations is necessary to better understand and more accurately plan for the impacts of climate change on a building's energy use. Architects in the twenty-first century strive to create sustainable building designs with efficient building envelopes that will benefit both the users and the built environment. With this current emphasis on reducing building energy use and on sustainability, it is essential to understand how these buildings will fare in the future. Will the design that is sustainable now still be so in thirty or fifty years? The most effective way to answer this today—to grasp the impacts of climate change—is to use future weather data in simulations to study the performance of the building in the present and the future.

Appendix A

Resources on Global Dimming and Brightening

Further information on global dimming and brightening can be found in the following journal articles,

Wild, Martin, and Edgar Schmucki. "Assessment of global dimming and brightening in IPCC-AR4/CMIP3 models and ERA40." *Climate Dynamics*, 2010: 1671-1688.

Wild, Martin. "Enlightening Global Dimming and Brightening." *Bulletin of the American Meteorological Society,* 2012: 27-37.

Appendix B

DesignBuilder Parameter Settings

The following are the DesignBuilder parameter settings for the HNEI Frog classroom building:

<u>-Construction Tab</u>

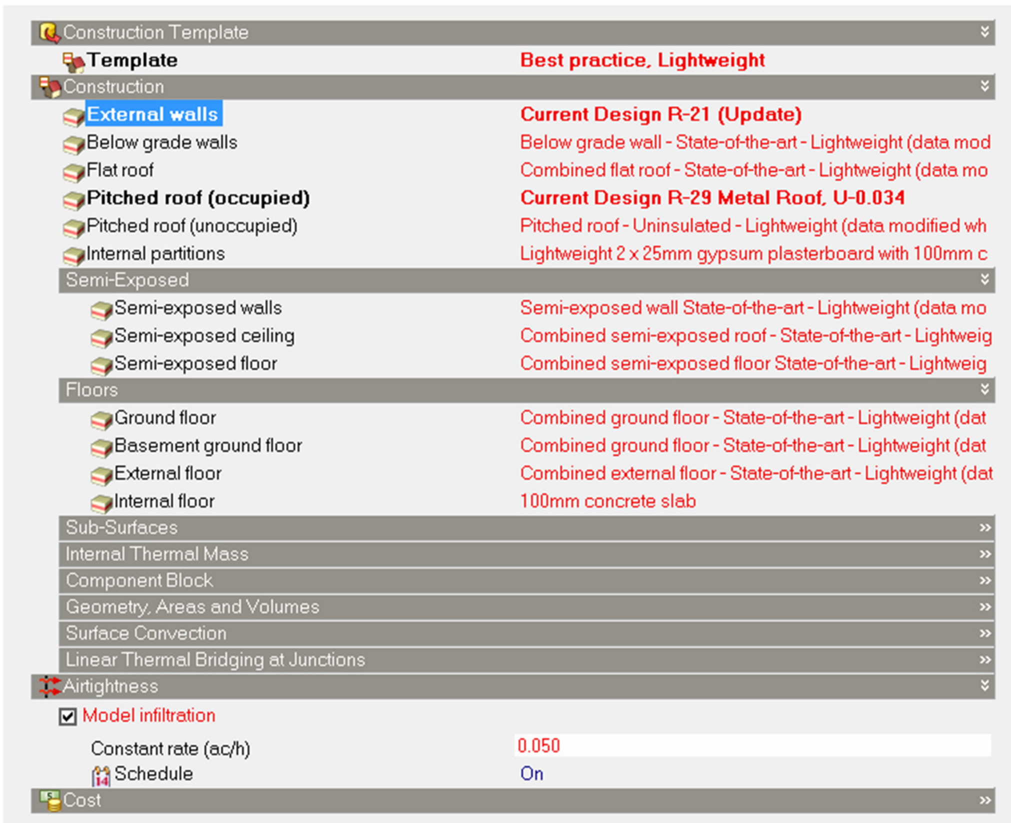


Figure 78. DesignBuilder parameter settings: Construction Tab
Source: Author

-Opening Tab

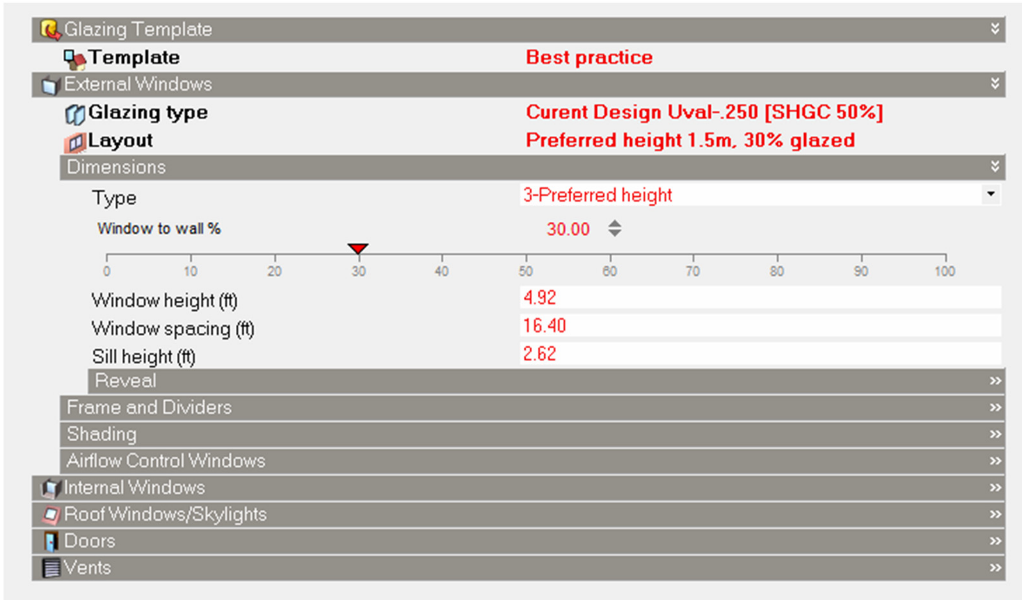


Figure 79. DesignBuilder parameter settings: Opening (window glazing) Tab

-Lighting Tab"

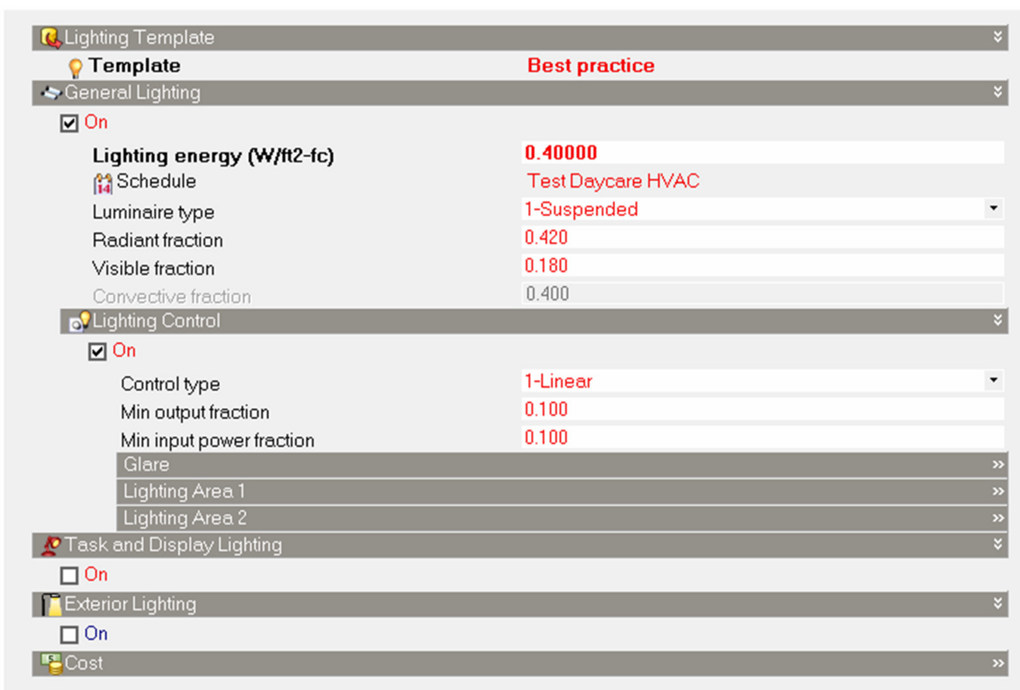


Figure 80. DesignBuilder parameter settings: Lighting Tab

Appendix C

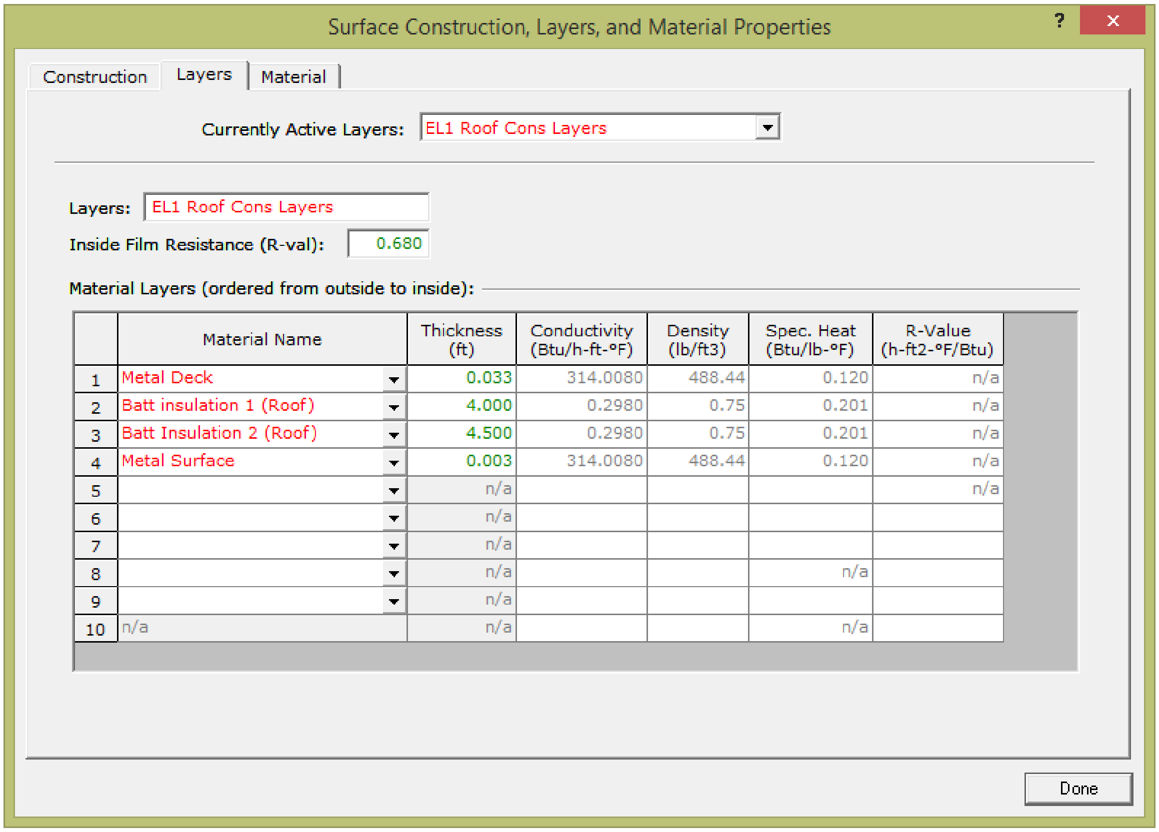
Current Design Building Envelope Material Data

Table 36. Current Design: exterior wall assembly and material data (R-21, U-0.044)

Exterior	**7/8 in. Portland Cement & Plaster + Metal Lath**			
		Thickness:	0.073	Feet
		Conductivity:	0.416	Btu-in/h-ft2-F
		Density:	109.870	lb/ft3
		Specific Heat:	0.201	Btu/lb-F
	1/2 in. OSB Sheathing			
		Thickness:	0.042	Feet
		Conductivity:	0.061	Btu/h-ft-F
		Density:	40.578	Lb/ft3
		Specific Heat:	0.449	Btu/Lb-F
	Air gap 50 mm			
		Thickness:	1.667	Feet
		Conductivity:	0.173	Btu/h-ft-F
		Density:	62.428	Lb/ft3
		Specific Heat:	0.239	Btu/Lb-F
	1/2 in. Plywood Shim			
		Thickness:	0.042	Feet
		Conductivity:	0.052	Btu/h-ft-F
		Density:	28.717	Lb/ft3
		Specific Heat:	0.449	Btu/Lb-F
	5 1/2 in. R-21 Batt Insulation (R-16)			
		Thickness:	0.458	Feet
		Conductivity:	0.025	Btu/h-ft-F
		Density:	0.749	Lb/ft3
		Specific Heat:	0.201	Btu/Lb-F
	5/8 in OSB Sheathing			
		Thickness:	0.052	Feet
		Conductivity:	0.061	Btu/h-ft-F
		Density:	40.578	Lb/ft3
		Specific Heat:	0.449	Btu/Lb-F
Interior	**7/8 in. Portland Cement & Plaster + Metal Lath**			
		Thickness:	0.073	Feet
		Conductivity:	0.416	Btu-in/h-ft2-F
		Density:	109.870	lb/ft3
		Specific Heat:	0.201	Btu/lb-F

Table 37. Current Design: roof assembly and material data (R-29 U-0.034)

Exterior	**Metal Deck**			
		Thickness:	0.033	Feet
		Conductivity:	26.2	Btu-in/h-ft2-F
		Density:	488.437	lb/ft3
		Specific Heat:	0.120	Btu/lb-F
	R-Batt Insulation			
		Thickness:	0.333	Feet
		Conductivity:	0.025	Btu/h-ft-F
		Density:	0.749	Lb/ft3
		Specific Heat:	0.201	Btu/Lb-F
	R-Batt Insulation			
		Thickness:	0.375	Feet
		Conductivity:	0.025	Btu/h-ft-F
		Density:	0.749	Lb/ft3
		Specific Heat:	0.201	Btu/Lb-F
Interior	**Metal Surface**			
		Thickness:	0.003	Feet
		Conductivity:	26.2	Btu/h-ft-F
		Density:	488.437	Lb/ft3
		Specific Heat:	0.120	Btu/Lb-F


Surface Construction, Layers, and Material Properties

Construction | Layers | Material

Currently Active Layers: EL1 Roof Cons Layers

Layers: EL1 Roof Cons Layers

Inside Film Resistance (R-val): 0.680

Material Layers (ordered from outside to inside):

	Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
1	Metal Deck	0.033	314.0080	488.44	0.120	n/a
2	Batt insulation 1 (Roof)	4.000	0.2980	0.75	0.201	n/a
3	Batt Insulation 2 (Roof)	4.500	0.2980	0.75	0.201	n/a
4	Metal Surface	0.003	314.0080	488.44	0.120	n/a
5		n/a				n/a
6		n/a				
7		n/a				
8		n/a			n/a	
9		n/a				
10	n/a	n/a			n/a	

Done

Figure 81. Current Design: roof construction assembly layers (eQuest)

Appendix D

ASHRAE Design Building Envelope Material Data

Table 38. ASHRAE Design: exterior wall assembly and material data (R-13 U-0.089)

Exterior	**3/4 in Stucco**			
		Thickness:	0.063	Feet
		Conductivity:	0.781	Btu-in/h-ft2-F
		Density:	115.991	lb/ft3
		Specific Heat:	0.201	Btu/lb-F
	5/8 in Gypsum Board			
		Thickness:	0.052	Feet
		Conductivity:	0.093	Btu/h-ft-F
		Density:	39.954	Lb/ft3
		Specific Heat:	0.275	Btu/Lb-F
	Board Insulation (Glass fiber board)			
		Thickness:	0.127	Feet
		Conductivity:	0.021	Btu/h-ft-F
		Density:	9.989	Lb/ft3
		Specific Heat:	0.201	Btu/Lb-F
	Board Insulation (Glass fiber board			
		Thickness:	0.061	Feet
		Conductivity:	0.021	Btu/h-ft-F
		Density:	9.989	Lb/ft3
		Specific Heat:	0.201	Btu/Lb-F
Interior	**5/8 in Gypsum Board**			
		Thickness:	0.052	Feet
		Conductivity:	0.093	Btu/h-ft-F
		Density:	39.954	Lb/ft3
		Specific Heat:	0.275	Btu/Lb-F

Table 39. ASHRAE Design: roof assembly and material data (R-19 U-0.065)

Exterior	**Metal Deck**		
	Thickness:	0.033	Feet
	Conductivity:	26.2	Btu-in/h-ft2-F
	Density:	488.437	lb/ft3
	Specific Heat:	0.120	Btu/lb-F
	Glass-fiber Batt Insulation		
	Thickness:	0.363	Feet
	Conductivity:	0.025	Btu/h-ft-F
	Density:	0.201	Lb/ft3
	Specific Heat:	0.749	Btu/Lb-F
Interior	**Metal Surface**		
	Thickness:	0.003	Feet
	Conductivity:	26.2	Btu/h-ft-F
	Density:	488.437	Lb/ft3
	Specific Heat:	0.120	Btu/Lb-F

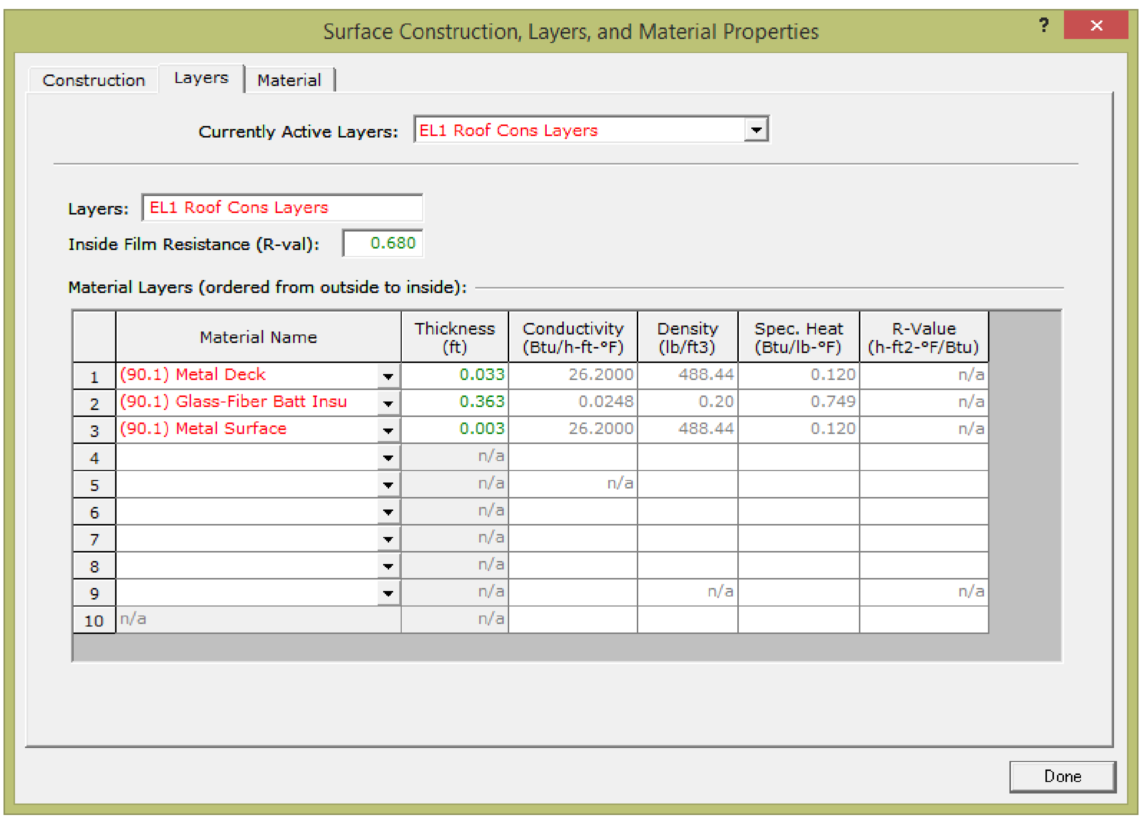


Figure 82. ASHRAE Design: roof construction assembly layers (eQuest)

Appendix E

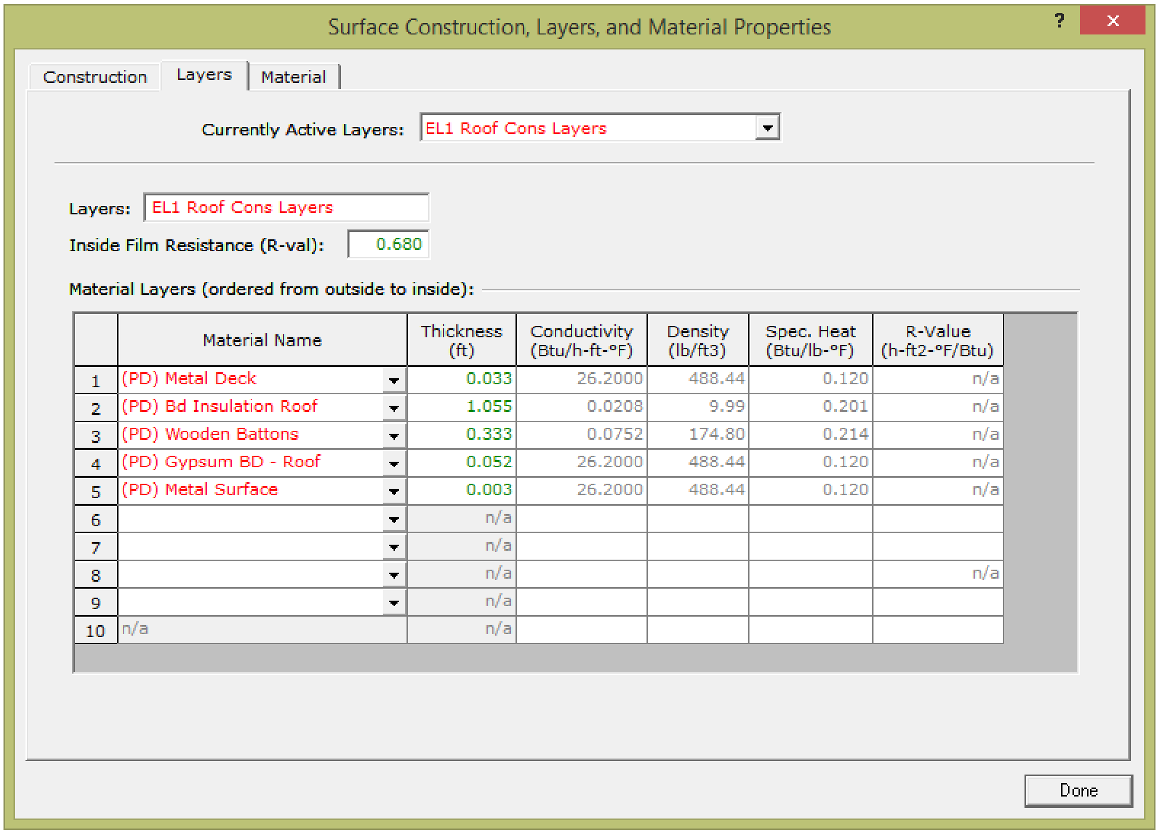
Proposed Design Building Envelope Material Data

Table 40. Proposed Design: exterior wall assembly and material data (R-35 U-0.029)

Exterior	**3/4 in Stucco**			
		Thickness:	0.063	Feet
		Conductivity:	0.781	Btu-in/h-ft2-F
		Density:	115.991	lb/ft3
		Specific Heat:	0.201	Btu/lb-F
	5/8 in Gypsum Board			
		Thickness:	0.052	Feet
		Conductivity:	0.093	Btu/h-ft-F
		Density:	39.954	Lb/ft3
		Specific Heat:	0.275	Btu/Lb-F
	Board Insulation (Glass fiber board)			
		Thickness:	0.333	Feet
		Conductivity:	0.021	Btu/h-ft-F
		Density:	9.989	Lb/ft3
		Specific Heat:	0.201	Btu/Lb-F
	Board Insulation (Glass fiber board			
		Thickness:	0.350	Feet
		Conductivity:	0.021	Btu/h-ft-F
		Density:	9.989	Lb/ft3
		Specific Heat:	0.201	Btu/Lb-F
Interior	**5/8 in Gypsum Board**			
		Thickness:	0.052	Feet
		Conductivity:	0.093	Btu/h-ft-F
		Density:	39.954	Lb/ft3
		Specific Heat:	0.275	Btu/Lb-F

Table 41. Proposed Design: roof assembly and material data (R-65 U-0.018)

Exterior	**Metal Deck**			
		Thickness:	0.033	Feet
		Conductivity:	26.2	Btu-in/h-ft2-F
		Density:	488.437	lb/ft3
		Specific Heat:	0.120	Btu/lb-F
	Board Insulation (Glass fiber board)			
		Thickness:	1.055	Feet
		Conductivity:	0.021	Btu/h-ft-F
		Density:	9.989	Lb/ft3
		Specific Heat:	0.201	Btu/Lb-F
	Wooden Battons			
		Thickness:	0.333	Feet
		Conductivity:	0.075	Btu/h-ft-F
		Density:	174.798	Lb/ft3
		Specific Heat:	0.214	Btu/Lb-F
	Gypsum Board			
		Thickness:	0.052	Feet
		Conductivity:	26.2	Btu/h-ft-F
		Density:	488.437	Lb/ft3
		Specific Heat:	0.120	Btu/Lb-F
Interior	**Metal Surface**			
		Thickness:	0.003	Feet
		Conductivity:	26.2	Btu/h-ft-F
		Density:	488.437	Lb/ft3
		Specific Heat:	0.120	Btu/Lb-F



	Material Name	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
1	(PD) Metal Deck	0.033	26.2000	488.44	0.120	n/a
2	(PD) Bd Insulation Roof	1.055	0.0208	9.99	0.201	n/a
3	(PD) Wooden Battons	0.333	0.0752	174.80	0.214	n/a
4	(PD) Gypsum BD - Roof	0.052	26.2000	488.44	0.120	n/a
5	(PD) Metal Surface	0.003	26.2000	488.44	0.120	n/a
6		n/a				
7		n/a				
8		n/a				n/a
9		n/a				
10	n/a	n/a				

Figure 83. Proposed Design: roof construction assembly layers (eQuest)

Appendix F

Cooling Load Comparison for Current Design (Winter vs Summer)

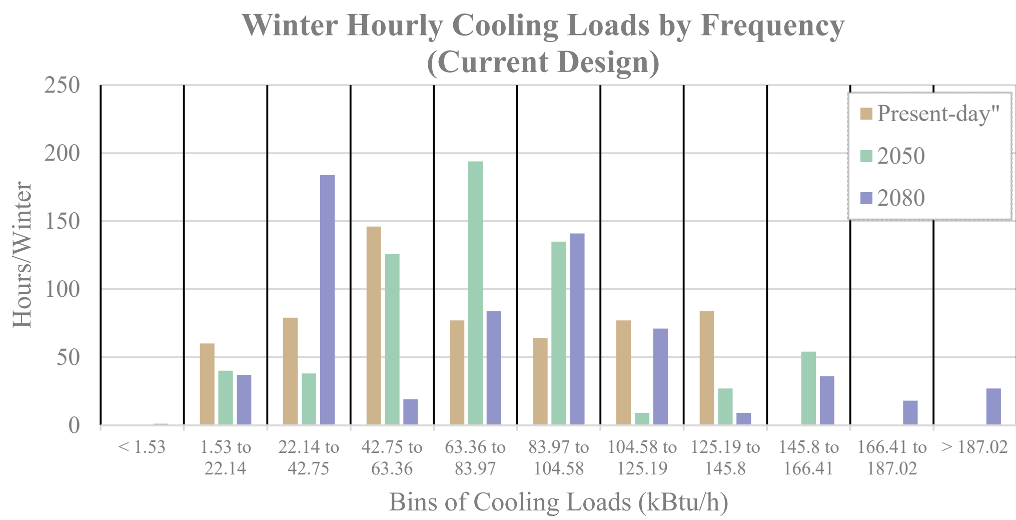


Figure 84. Winter hourly cooling loads frequency for Current Design
Source: Author

Table 42. Number of hours/winter of occurrences for the bin ranges for Current Design

	Bins of Cooling Loads (kBtu/h)										
	<1.53	1.53 to 22.14	22.14 to 42.75	42.75 to 63.36	63.36 to 83.97	83.97 to 104.58	104.58 to 125.19	125.19 to 145.8	145.8 to 166.41	166.41 to 187.02	>187.02
Present-day hours per winter	0	60	79	146	77	64	77	84	0	0	0
2050 hours per winter	0	40	38	126	194	135	9	27	54	0	0
2080 hours per winter	1	37	184	19	84	141	71	9	36	18	27

Source: Author

The above figure 84 shows a higher range of cooling loads for the winter than in the summer months in figure 85 for the Current Design model in all three time periods. The amount of cooling energy required for the winter months was 42,950 kBtu/yr for present-day, 48,529 kBtu/yr for 2050, and 50,400 kBtu/yr for 2080. The results show a steady increase of cooling load hours and annual energy use for the Current Design in the winter months across the time periods.

The formula used to compute amount of cooling energy required is as follows:

Hours/winter (h/winter) x Average Bin of cooling load (kBtu/h) = Energy (kBtu/winter)

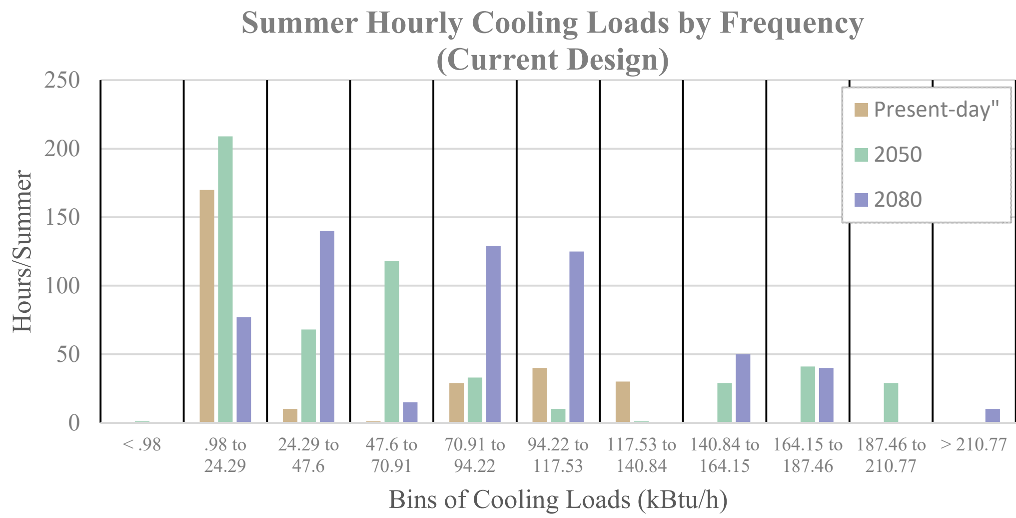


Figure 85. Summer hourly cooling loads frequency for Current Design
Source: Author

Table 43. Number of hours/summer of occurrences for the bin ranges for Current Design

	Bins of Cooling Loads (kBtu/h)										
	<.98	.98 to 24.29	24.29 to 47.6	47.6 to 70.91	70.91 to 94.22	94.22 to 117.53	117.53 to 140.84	140.84 to 164.15	164.15 to 187.49	187.46 to 210.77	>210.77
Present-day hours per summer	0	170	10	1	29	40	30	0	0	0	0
2050 hours per summer	1	209	68	118	33	10	1	29	41	29	0
2080 hours per summer	0	77	140	15	129	125	0	50	40	0	10

Source: Author

The above figure 85 shows a lower range of cooling loads in the summer than in the winter months in figure 84 for the Current Design model in all three time periods. The amount of cooling energy required for the summer months was 13,071 kBtu/yr for present-day, 33,395 kBtu/yr for 2050, and 47,660 kBtu/yr for 2080. The results show a steady increase of cooling load hours and annual energy use for the Current Design in the summer months across the time periods.

The formula used to compute amount of cooling energy required is as follows:

Hours/summer (h/summer) x Average Bin of cooling load (kBtu/h) = Energy (kBtu/summer)

Appendix G

Cooling Load Comparison for Proposed Design (Winter vs Summer)

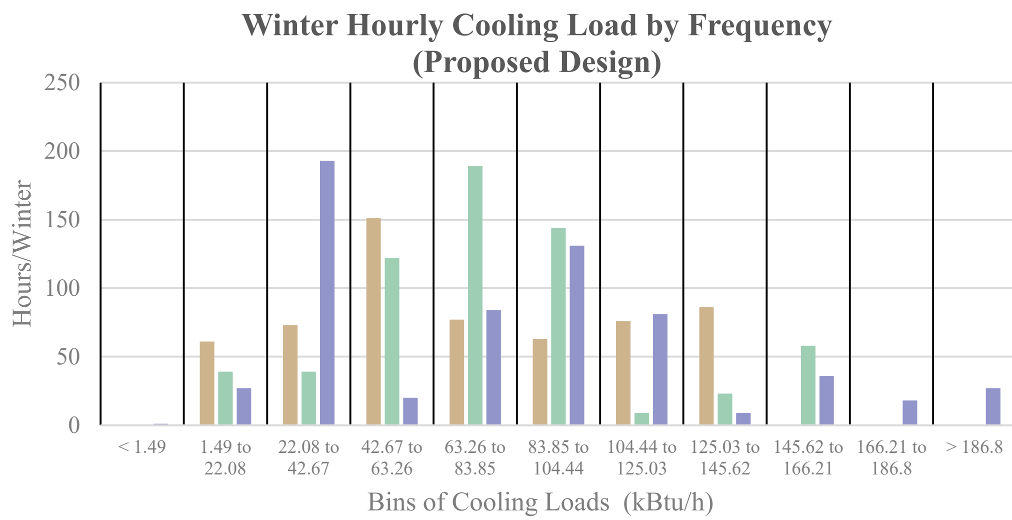


Figure 86. Winter hourly cooling loads frequency for Proposed Design
Source: Author

Table 44. Number of hours/winter of occurrences for the bin ranges for Proposed Design

	Bins of Cooling Loads (kBtu/h)										
	<1.49	1.49 to 22.08	22.08 to 42.67	42.67 to 63.26	63.26 to 83.85	83.85 to 104.44	104.44 to 125.03	125.03 to 145.62	145.62 to 166.21	166.21 to 186.8	>186.8
Present-day hours per winter	0	61	73	151	77	63	76	86	0	0	0
2050 hours per winter	0	39	39	122	189	144	9	23	58	0	0
2080 hours per winter	1	27	193	20	84	131	81	9	36	18	27

Source: Author

The above figure 86 shows a higher range of cooling loads in the winter than in the summer months figure 87 for the Proposed Design model in all three time periods. The amount of cooling energy required for the winter months was 43,032 kBtu/yr for present-day, 48,830 kBtu/yr for 2050, and 50,761 kBtu/yr for 2080. The results show a steady increase of cooling load hours and annual energy use for the Proposed Design in the winter months across the time periods.

The formula used to compute total amount of cooling energy required is as follows:

Hours/winter (h/winter) x Average Bin of cooling load (kBtu/h) = Energy (kBtu/winter)

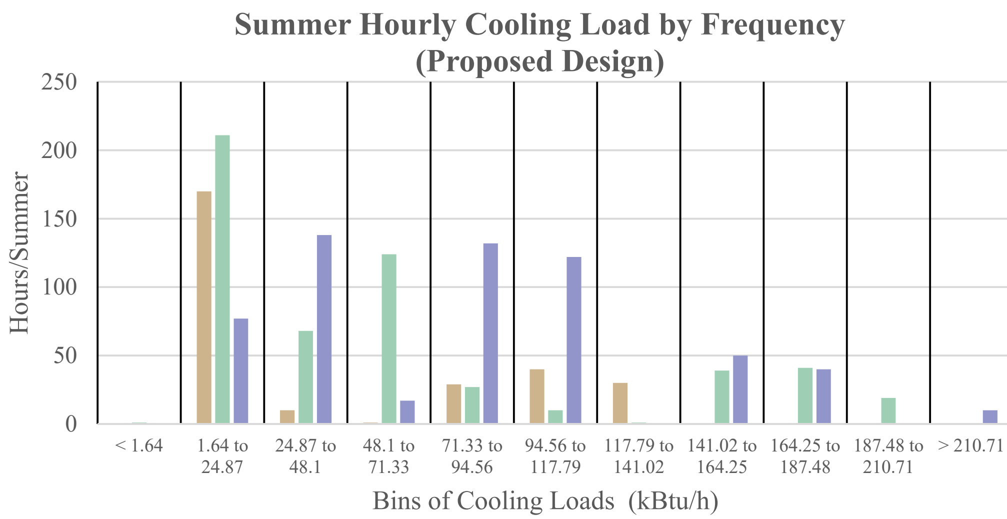


Figure 87. Summer hourly cooling loads frequency for Proposed Design
Source: Author

Table 45.Number of hours/summer of occurrences for the bin ranges for Proposed Design

	Bins of Cooling Loads (kBtu/h)										
	<1.64	1.64 to 24.87	24.87 to 48.1	48.1 to 71.33	71.33 to 94.56	94.56 to 117.79	117.79 to 141.02	141.02 to 164.25	164.25 to 187.48	187.48 to 210.71	>210.71
Present-day hours per summer	0	170	10	1	29	40	30	0	0	0	0
2050 hours per summer	1	211	68	124	27	10	1	39	41	19	0
2080 hours per summer	0	77	138	17	132	122	0	50	40	0	10

Source: Author

The above figure 87 shows a lower range of cooling loads in the summer than in the winter months in figure 86 for the Proposed Design model in all three time periods. The amount of cooling energy required for the winter months was 13,211 kBtu/yr for present-day, 33,058 kBtu/yr for 2050, and 47,860 kBtu/yr for 2080. The results show a steady increase of cooling load hours and annual energy use for the Proposed Design in the summer months across the time periods.

The formula used to compute total amount of cooling energy required is as follows:

Hours/summer (h/summer) x Average Bin of cooling load (kBtu/h) = Energy (kBtu/summer)

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